



TP 9542E

DEVELOPMENT OF AN IN-FIELD AUTOMATIC
CRACK DETECTION SYSTEM FOR RAILROAD WHEELS

PHASE 1 - FINAL REPORT
AUTOMATIC WHEEL DEFECT DETECTION
TECHNOLOGIES ASSESSMENT

PREPARED FOR THE
TRANSPORTATION DEVELOPMENT CENTRE

POLICY AND COORDINATION GROUP
TRANSPORT CANADA

BY

J.L. ALLARD & P.W. EYRE
ENVIRONMENT DIVISION

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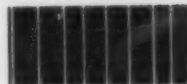
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17. Abstract The objective of the work conducted was to evaluate the effectiveness of acoustic and vibration measurement and analysis techniques as a basis for a field system capable of automatically identifying and characterizing cracks and shelling in railway vehicle wheels. To meet this objective, a background survey was undertaken comprising literature review, telephone interviews, and visits. Theoretical studies were conducted. New and defective wheels were laboratory and shop tested to evaluate key parameters. The background study showed that despite recent improvements in rail safety practice and equipment reliability, a significant number of defective wheels pass undetected and result in derailments. Defects of interest also included flats and wear. Attempts have been made by researchers to develop automatic inspection devices for use in the field. The 400 kHz ultrasonic systems in service with Florida East Coast Railway and under development for the Deutsche Bundesbahn are the most advanced, although their applications are limited. Tests with acoustic systems showed the need to excite wheels at frequencies above 10 kHz (i.e. above the audible range). All defects which might lead to work failure can be identified by existing technology under laboratory conditions using vibration analysis. A practical field system has yet to be developed. Further basic tests are required.			
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17. Résumé L'objectif de cette étude est d'évaluer l'efficacité des techniques de mesures et d'analyses, dans le domaine des fréquences audibles, comme bases d'un système automatisé de détection de la présence et de la taille de défauts tels les fissures et l'écaillage dans les roues du matériel roulant ferroviaire. Afin d'atteindre cet objectif, une revue générale de l'état de la technologie a été faite à l'aide d'articles scientifiques et d'entrevues avec des spécialistes. Aussi, des mesures en laboratoire et en atelier ont été faites sur des roues en bon et en mauvais état afin d'évaluer, de façon préliminaire, le potentiel de certaines techniques acoustiques visant à détecter ces défauts. L'étude préliminaire montre qu'en dépit des récents développements visant à accroître la sécurité et la fiabilité du matériel ferroviaire, un nombre significatif de roues présentant des défauts non acceptables demeurent en service et entraînent des déraillements. Les défauts considérés incluent également les plats et l'usure de la roue. Des tentatives ont été réalisées par des chercheurs afin de développer des systèmes automatiques d'inspection des roues en continu utilisables dans les cours de triage. Les réalisations les plus avancées au point de vue technologique et pratique utilisent des ultra-sons à des fréquences de l'ordre de 400 kHz et sont en usage au "Florida East Coast Railway" et en développement à la "Deutsche Bundesbahn" en Allemagne de l'Ouest. Ces technologies sont opérationnelles bien qu'ayant leurs limites. Les essais réalisés dans le domaine des fréquences audibles confirment un potentiel intéressant pour la détection de défauts multiples. La détection de petites fissures (de l'ordre de 6 mm) à l'aide de cette technologie semble limitée et requiert une analyse à des fréquences plus élevées.			
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PROJECT TEAM

The project team involved in this first phase of technology assessment was composed of the following personnel:

- J.L. Allard
- F.W. Eyre
- J. Rennie
- Y. Champoux
- C. Chamberland
- P. Mulocher

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SUMMARY

Improvements in rail safety and equipment design during the last decade have reduced the incidence of train derailments. However, although present visual inspection techniques successfully locate 99.5% of condemnable wheels, the remaining 1% pass undetected, usually during the winter. The desirability of further improvements in safety standards together with present trends towards increased automation in railroad operations has generated an interest in the development of field-installed automated wheel inspection systems capable of inspecting the wheels on a train in motion.

The objective of the project was to evaluate the effectiveness of acoustic and vibration measurement and analysis techniques as the basis for a system capable of automatically identifying and sizing defects in railway vehicle wheels.

To accomplish this objective, work has been divided into two phases. The first phase, covered by the present report, comprised a definition of the defects of concern, a background survey to ascertain state of the art in development of automated wheel defect detection systems, theoretical analysis of wheel response to excitation, and laboratory and shop tests to determine the effects of defects on wheel vibrational signature.

The defects to be identified comprise cracks originating at different locations, shelling, excessive wear and "flats" on the treads caused by sliding of wheels on rails due to locked brakes. Acceptance/rejection criteria for cracks detected by automatic devices pose problems. Devices of interest are based on vibration analysis principles and detect general crack characteristics - width, depth and location. Present inspection standards derived from years of practical experience are based on visual methods and only take into account observable length. Crack depth or presence of sub-surface defects are not taken into account. Automated inspection devices are able to identify crack profiles below the wheel surface. However, inadequate data exists to define acceptable cracks since both crack depth and subsequent rate of propagation are dependent on wheel history and wheel (axle) loading. Rejection of wheels with any identifiable crack is unrealistic since virtually all wheels develop hairline surface cracks after some service.

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SUMMARY (Cont'd)

A survey of work done to date, principally at the University of Houston, showed that despite extensive efforts with acoustic systems an acceptable false alarm rate was not achieved. A prototype system was installed in the Southern Pacific Railroad. This system used a comparative signal processing technique which compared the signatures of two wheels on a common axle, both excited by spring-loaded hammers at nominally the same time. Excitation frequencies were below 10 kHz. An ultrasonic (400 kHz excitation) system developed by Wheelfax and installed in the Florida East Coast Railway has worked to the operators' satisfaction. It can detect cracks and shelling in the tread rim and flange areas where the majority (but not all) of such defects occur. A more advanced ultrasonic system (also with 400 kHz excitation) has been developed for the Deutsche Bundesbahn and a prototype reportedly works well for passenger train service. It has the same limitations of applicability as the Wheelfax unit.

SNC conducted a theoretical analysis of the problem, together with laboratory tests at the University of Sherbrooke and shop tests in CN's Pointe St-Charles facility with new and defective wheels. Vibrations in the wheels under test were induced by impacting with a hammer instrumented so that the input excitation was known. Signal processing was based upon an analysis of the measured output signal. This approach contrasted with the method used at the University of Houston where two wheels on a common axle were impacted simultaneously, and the output signals were compared to see if there were significant differences.

This analytical approach removes significant unknown variables relative to the earlier comparative method and has the potential to reduce the false-alarm rate substantially. Testing to determine the effect of hammer design on the input showed that considerable care is required in hammer design to ensure valid data is obtained.

Tests at excitation frequencies below 10 kHz showed that defects had a significant effect on wheel signature but that characterization of the defects based on the output signature in most cases involving small cracks proved difficult. It was noted that as the excitation frequency increased, this problem was reduced. It would appear that at frequencies in the 25-100 kHz range, all defect characterization should be possible.

SUMMARY (Cont'd)

The results of the preliminary studies on the excitation hammer suggest that other excitation devices should be considered in order to reach around 100 kHz. Other transducers capable of measuring high frequencies without being saturated with low frequencies should also be considered. Signal reception by microphones or accelerometers would be practical.

Shop tests with wheels rolling on rails showed that rail-mounted accelerometers could identify wheel-tread surface defects.

The work reported is an advance over work done by others in the acoustic field and shows the potential for development of an automated field inspection system to detect all wheel defects with a final output compatible with Canadian railroad operational practices. Such a system would not necessarily be based on a single vibration excitation/analysis technique.

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SOMMAIRE

Les améliorations apportées durant la dernière décennie au design et à la sécurité du matériel ferroviaire ont entraîné une diminution des déraillements. Cependant, bien que les techniques d'inspection visuelles implantées à ce jour permettent le retrait de 99.5 % des roues considérées comme défectueuses (ou non standard), il reste 0,5 % de roues non acceptables qui ne sont pas détectées, principalement pendant l'hiver. La nécessité d'améliorer encore les standards au point de vue sécuritaire ainsi que la tendance actuelle à automatiser les opérations ferroviaires ont suscité beaucoup d'intérêt pour un dispositif d'inspection en continu qui pourrait examiner les roues d'un train en mouvement dans une gare de triage.

L'objectif de ce projet est d'évaluer l'efficacité de la technologie acoustique et vibratoire, dans la gamme des fréquences audibles, pour détecter automatiquement les défauts des roues du matériel ferroviaire. Cette technique devra identifier le type de défaut et en déterminer la dimension afin d'en établir le degré d'acceptabilité au poste d'inspection.

Cet objectif sera atteint en deux phases. La première, faisant l'objet du présent rapport, comprenait: l'identification et la taille acceptable des défauts, l'avancement dans la mise au point d'un dispositif automatique de détection des défauts dans le matériel roulant ferroviaire, l'analyse théorique de la réponse d'une roue soumise à une excitation vibratoire, et des mesures en laboratoire et en atelier pour déterminer l'influence de ces défauts sur la signature vibratoire d'une roue.

Les principaux types de défauts devant être identifiés sont les fissures (quel que soit leur siège: surface de roulement, jante, plateau, etc.), l'écaillage, l'usure excessive et les plats à la surface de roulement et associés au glissement des roues sur les rails en cas de freinage de durée anormale.

Dans le cas des fissures, les critères d'acceptabilité ou de rejet en vigueur sont difficiles à appliquer en raison de leur ambiguïté. Basé sur l'analyse de la signature vibratoire de la roue, le dispositif désiré permettra de détecter les caractéristiques des fissures (largeur, profondeur et emplacement). Les standards basés sur l'inspection visuelle des roues nécessitent des années d'expérience pratique afin d'interpréter comme indice principal la longueur apparente de la fissure et ne permet pas de tenir compte de la profondeur des fissures visibles ni des fissures non apparentes situées sous la surface de roulement.

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SOMMAIRE (Suite)

Les dispositifs de détection automatique de défauts peuvent détecter les fissures situées sous la surface de roulement de la roue. Cependant, on se heurte, pour pouvoir mettre au point une approche plus raffinée de détection des fissures, à l'absence de données permettant de définir les critères d'acceptabilité puisque la profondeur des fissures et leur vitesse de propagation dépendent des cycles de chargement (thermique et mécanique) de la roue.

D'autre part, le rejet de toutes les roues ayant des fissures apparentes n'est pas envisageable puisque pratiquement toutes les roues ont des microfissures après un certain temps d'utilisation.

Les recherches réalisées à l'Université de Houston sur les fréquences audibles indiquent un nombre de fausses alarmes (détection de défauts sur une roue en bonne condition) trop élevé pour en justifier l'adoption. Un prototype basé sur cette technologie a été essayé par la compagnie "Southern Pacific Railroad". La technique d'analyse utilisée consistait à comparer la signature des deux roues d'un même axe à l'aide de différentes procédures de traitement du signal, les roues étant excitées mécaniquement à l'aide d'un marteau actionné par un mécanisme à came avec retour contrôlé par un ressort pour des fréquences maximales d'excitation inférieures à 10 kHz.

Parallèlement, un système à ultra-sons (fréquence de l'ordre de 400 kHz) a été commercialisé sous la marque Wheelfax et installé à la compagnie "Florida East Coast Railway" où il répond aux critères des propriétaires. Ce système permet de détecter fissures et écaillage sur la surface de roulement et la jante de la roue, là où l'on observe la majorité des défauts.

Un système à ultra-sons plus raffiné et d'une technologie plus avancée (fonctionnant dans la même plage de fréquences) a été mis au point en Allemagne de l'Ouest pour la "Deutsche Bundesbahn". Les pilotes du projet nous ont indiqué qu'un prototype du dispositif automatique de détection des défauts donnait satisfaction sur une ligne passagers. Cette unité présente toutefois les mêmes limites d'applicabilité que celle de la "Wheelfax".

SOMMAIRE (Suite)

SNC a procédé à l'analyse théorique du problème, ainsi qu'à des tests dans les laboratoires de l'Université de Sherbrooke et dans les ateliers du CN à Pointe Saint-Charles avec des roues neuves et des roues considérées comme non acceptables. Les signaux mesurés étaient analysés suivant une approche analytique plutôt que comparative. De plus, les excitateurs (de type mécanique) utilisés étaient munis de capteurs de force ou d'accélération.

Cette approche a l'avantage d'éliminer certaines inconnues importantes (durée, contenu fréquentiel et énergétique de l'impact) qui n'avaient pas été mesurées par les chercheurs précédents.

Ces données supplémentaires, essentielles dans l'analyse de la signature des roues, pourraient permettre de réduire de façon significative le pourcentage de fausses alarmes obtenu à l'Université de Houston.

Les essais effectués avec différentes configurations des marteaux d'impact munis d'instruments ont confirmé l'importance des paramètres à contrôler pour obtenir une excitation et des signatures adéquates.

Les essais réalisés en excitant la roue à des fréquences inférieures à 10 kHz ont mis en évidence certaines disparités entre la signature d'une bonne roue et celle d'une roue défectueuse. Toutefois, la caractérisation des défauts, tels les fissures de moindre dimension, en se basant sur la signature des roues était ardue. L'excitation de roues à des fréquences supérieures (jusqu'à 25 kHz) a cependant permis de faire ressortir que les défauts étaient alors plus faciles à détecter (réflexion des impulsions sur la fissure). De plus, l'excitation à des fréquences allant jusqu'à 100 kHz qui sera étudiée à la phase 2 du projet devrait nous permettre de caractériser de façon satisfaisante les défauts de petite dimension.

Le résultat des analyses préliminaires sur des roues fissurées excitées par un marteau d'impact justifie des essais plus poussés à l'aide de mécanismes d'excitation pouvant atteindre des fréquences de l'ordre de 100 kHz et d'autres capteurs ayant la capacité d'éliminer les basses fréquences, lesquelles ont tendance à masquer les signaux à haute fréquence. Cependant, l'utilisation de capteurs tels que microphones et accéléromètres demeure utile.

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SOMMAIRE (Suite)

Des essais en atelier portant sur des jeux de roues en mouvement ont permis de mettre en évidence les défauts de la surface de roulement, à l'aide d'accéléromètres montés sur les rails.

Les études et analyses entreprises dans la première phase de cette étude préliminaire apportent certaines améliorations aux techniques utilisées par les pionniers de l'approche "acoustique" de la détection des défauts dans les roues du matériel roulant ferroviaire et prouvent le potentiel d'un dispositif automatisé compatible avec les installations ferroviaires canadiennes. Dans sa forme définitive, le dispositif idéal pourrait comprendre plusieurs mécanismes d'excitation et de mesure à une station donnée afin de caractériser l'ensemble des défauts présentant un intérêt pour la sécurité et la fiabilité du matériel roulant ferroviaire.

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1.0

INTRODUCTION

This report covers the first phase of a development program conducted under contract with Transport Canada's Transportation Development Centre, for an assessment of the suitability of acoustic frequency analysis techniques for the automatic detection of defects in railroad wheels in service.

In the present context, "defects" refers to cracks and shelling. Identification of excessive wear evident as thin flanges, high flanges, etc., may also be possible using acoustic frequency intensity analysis but has not been emphasized in the work undertaken.

The objective of this first phase of the program has been to establish the basis for future design of a field inspection unit. This field inspection unit would presumably be installed at the entrance/exit of a railroad yard, would perform the wheel inspections on moving trains under conditions to be expected in the Canadian environment, and might at some future time become part of an integral automated train inspection system.

A literature review, telephone interviews and field visits to determine previous development work and the state of the art of wheel crack detection were undertaken. Surveys were made of suitable instrumentation and preliminary tests were conducted to assess the applicability of acoustic intensity analysis and to determine signal processing requirements. Finally a preliminary cost estimate was developed for an inspection system based on a concept design to assess economic viability. The original contract work statement is given in Appendix A. On the basis of the work done, potential capabilities and limitations of a system have been identified and recommendations for future work are made.

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2.0 BACKGROUND

2.1 Problem Definition

Wheel Service Defects

The railroads have always been faced with the problem of how to minimize the number of train derailments, caused in part by broken (cracked) wheels.

On the basis of long experience with visual inspection, the Association of American Railroads (A.A.R) has developed criteria for acceptance or condemnation of defective wheels. These are described in the "Field Manual of the A.A.R. Interchange Rules" (1.1)*. The major Canadian railroads are members of the A.A.R. and comply with these criteria.

The defects which may be cause for wheel rejection, also referred to as "change-out", are given in Table 2.1. This information was taken from the Association of American Railroads Manual of Standards and Recommended Practices (1.2).

While the ultimate goal is to detect all defects automatically, the present study has concentrated on the detection of cracks and shelling.

Thermal cracks are caused by extended periods of brake shoe application and rapid cooling (1.3). The cracks appear as hair lines on the tread (or flange) and there are usually numerous cracks around the circumference of a damaged wheel. In many respects thermal cracks are the most critical because thermal cracking of wheels occurs relatively often.

Despite the barely visible exterior manifestation of this type of crack, below the surface it may occupy a sizeable fraction of the rim cross section. When a wheel with thermal cracks is withdrawn from service and subjected to metallurgical examination, the cracks are typically found to extend over about a square inch in area with the plane of the crack perpendicular to the surface.

The crack area is usually blackened, suggesting that the cracks may exist for long periods before progressing through the plate to cause a complete wheel failure. The final stage of the failure is probably a result of changes in the internal state of stress of the wheel.

* Numbers in parentheses refer to references given in Appendix C "General References and Bibliography".

TABLE 2.1

STEEL WHEEL DEFECTS

Defects which may be cause for removal of wheels from service.

<u>Defect</u>	<u>AAR "Why Made" Code</u>
Obsolete Material	07
Thin Flange	60
Vertical Flange	62
High Flange	64
Cracked or Broken Flange	66
Cracked or Broken Rim	68
Shattered Rim	71
Spread Rim	72
Thin Rim	73
Thermal Cracks	74
Shelled Tread	75
Built-Up Tread	76
Grooved Tread	77
Slid Flat	78
Scrape, Dent or Gouge in Wheel Plate	80
Out of Gage	81
Cracked or Broken Plate	83
Holes in Plate	84
Loose	85
Big Bore	86
Insufficient Hub Wall Thickness	87
Sub-surface Defect	88
Overheated	89

Source: Association of American Railroads, Manual of Standards and Recommended Practices, Section G., Ref. 1.2

2.1 Problem Definition (Cont'd)

Plate cracks are usually found as extensive bow-shaped fractures running round the hub and extending into the plate. Cracks in the plate can develop due to lateral stresses in service or tension due to rim heating during drag braking. This type of defect is not found as frequently as thermal cracking or overheating but some of the most catastrophic wheel failures have been ascribed to plate cracks. Plate cracks have been identified easily by acoustic signature inspection using the intensimetry technique discussed in Chapter 5.

Shelling occurs where pieces of metal break loose from the tread more or less continually around the wheel due to such causes as high mechanical loads, poor track, excessive speeds, etc. The phenomenon of spalling is caused by pieces of metal breaking out between thermal cracks and often has an appearance somewhat similar to shelling. The A.A.R. has no separate "Why Made" Code for spalling, and most reported shelling is believed to be a combination of shelling and spalling (1.3).

Shelling is of particular interest because of its high frequency of occurrence and the damage which a shelled wheel can cause to the track. Furthermore any cracks which accompany shelling may not be detected by visual inspection.

Flats are in general caused by sliding of a wheel on the track due to locked brakes. As with shelled wheels, a major concern is the damage which flats can cause to the track. From the point of view of detection, however, flats differ from shells in that flats do not have the irregular geometric forms of shells, and tend to give rise to a clear impact signature. Flats and shelling defects can be detected using microphones, accelerometers, or strain gauges mounted near or on the rail.

Thin flanges, high flanges and thin rims are caused by wear and/or machining to restore a good tread (on an otherwise condemned wheel) followed by wear. These wear-related defects are of interest because of their high frequency of occurrence and the necessity to remove a weakened wheel from service. Although the study has addressed cracks and shells, the need to identify worn wheels has been given some consideration.

Wheel wear is easily identified by acoustic techniques since the effect of normal service wear is to decrease the frequencies at which resonance peaks occur by a measurable amount. This is further discussed in section 5.4.2 "Effects of Tread Wear on Wheel Vibration Signature". Unfortunately, such characteristics

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2.1

Problem Definition (Cont'd)

would be difficult to apply in practice since each measurement requires an appropriate new wheel to provide a comparative reference.

The state of internal stress in a wheel is important since it determines whether a crack will propagate and at what rate. A means of determining internal stress on an automatic basis therefore would be a highly desirable feature of any wheel inspection system. Some evidence has been pinpointed in the literature (1.4) that changes in internal stress can be detected from acoustic signature inspection.

Defect Occurrence - Canadian Experience

Statistics for wheelset change-outs in Canadian railroad operations are not sufficiently detailed to permit a full analysis of all of the factors involved. Sample summary data is given in Table 2.2 for CN Rail in 1986 which may be taken as typical. From this it can be seen that the most common wheel service problem is shelling (97% of change-outs), the most common problem also identified by CP Rail and B.C. Rail, though not at the same frequency. It can also be seen that approximately 2% of wheelsets in service were identified as defective per annum. Finally, it is noted that compared to 122 wheelset changeouts located visually and classified by A.A.R. codes 68, 74 and 83, there were on average 5 failures, i.e. 4% of the defects which occurred within these categories passed undetected.

For all of Canada for the same year there were 12 derailments due to wheel failures. Railway property damage was reported (5) at over \$1.5M. Costs including lost business due to delays, damage to cargo, and non-railway property damage are not included in this figure.

The foregoing observations take no account of service, wheel type, regional or seasonal effects and serve only as an indication of the level of the problem.

Trends

. Wheel Failures

During the last 6-8 years the rate of derailments per billion ton-miles has been declining due to improvements in wheel technology and operations. It is reasonable to expect still further improvements in the future.

TABLE 2.2

SAMPLE STATISTICS OF WHEEL CRACKING & SHELLING FOR CN RAIL- 1986

(1) SERVICE SUMMARY

Total Service	167 billion gross ton-miles
Average Loads	5,307 gross tons/train 2,782 net tons/train
Total Fleet	85,000 (approx.) cars (= 340,000 wheelsets)

(2) WHEELSET CHANGE-OUTS

<u>A.A.R. Code</u>		<u>No. of Defective Wheelsets</u>	<u>(%)</u>
66	Cracked or broken flange	61	(1.0)
68	Cracked or broken rim	80	(1.3)
74	Thermal cracks	38	(0.6)
75	Shelled tread	6077	(96.9)
83	Cracked or broken plate	4	(0.1)
	Others	5	(0.1)
	TOTAL	6265	(100%)

(3) DERAILMENTS (1984-1986, incl.)

<u>A.A.R. Code</u>			
68	Cracked or broken rim	2	(13.3)
74	Thermal cracks	11	(73.4)
83	Broken plates	<u>2</u>	(13.3)
	3-year total	15	(100%)
	Single Year Average	5	

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2.1 Problem Definition (Cont'd)

Trends (Cont'd)

- Automation trends

Automated wheel inspection is a logical element to be addressed in the automation of railroad operations.

- Pressure for productivity gains

An automated system has the potential to contribute to increased productivity - more frequent inspection/more reliable inspection/lower cost per operation, and high level of identification of defects before accidents can occur.

- Operational trends

The operational trends are towards more demanding use of equipment - higher loadings for freight train equipment; higher speeds for passenger equipment. These demands require more precise control of equipment quality.

2.2 Wheel Crack Detection

The traditional methods of inspection for defects in railroad wheels in service have been predominantly visual inspection, and "wheel tapping" wherein the inspector taps the wheel with a hammer and listens to the resulting "ring".

Visual inspection is in use worldwide. It is an easy method to apply and personnel can become experienced with little training. Tapping requires more experience, a "tuned ear", and a greater level of subjective judgement. Both methods suffer common disadvantages:

- uneven quality/subjective opinion;
- occasional non-visibility of cracks;
- significant cost of personnel;
- difficulty of inspection in adverse weather conditions;
- need for the cars to be stationary;
- significant improvements in fault detection cannot reasonably be expected.

2.2

Wheel Crack Detection (Cont'd)

Attempts have been made by researchers during the past decade to develop suitable automated inspection devices but to date none have been wholly successful. Systems based on ultrasonic frequency excitation have only been able to detect tread surface cracks. Systems based on acoustic frequency excitation have experienced difficulties in field applications. Both systems have experienced high false-alarm rates.

The problem then, is to develop a system design which will reliably determine whether or not cracks, shelling and/or other condemnable defects are present in wheels on the cars of a train. The logical location for installation of such a system is at the entrance to a yard where personnel can be notified and instructed to take corrective action. The system must include notification and identification sub-systems. A fixed inspection system should logically be capable of inspecting trains in motion at their normal operating yard speeds as they pass the inspection point.

The range of developments in non-destructive test techniques that could be used for wheel defect detection and identification includes magnetic-particle, dye penetrant, radiographic, ultrasonic, eddy current, microwave, infrared, and acoustic techniques.

While most of the methods could be used in the controlled environment of a maintenance shop, the implicit requirement that a field system should be able to detect defects while the train, and therefore the wheel, is in motion effectively eliminates all except those associated with evaluation of vibration signatures. Hence the first objective of the project test work has been to evaluate acoustic and higher frequency vibration test techniques, with the focus on the recent technological development of intensity analysis.

The types of waves which can exist in a solid and their relevance to wheel crack determination are discussed in Appendix B. In summary, two frequency regimes, acoustic (0-20,000 Hz) and ultrasonic (20,000 Hz to the megahertz range), are of interest.

Elements of Acoustic Signature Analysis

The major components of an Acoustic Wheel Signature (AWS) system are illustrated schematically in Figure 2.1. The wheel to be analysed, is excited by some means in order to generate within the wheel a series of pulse waves.

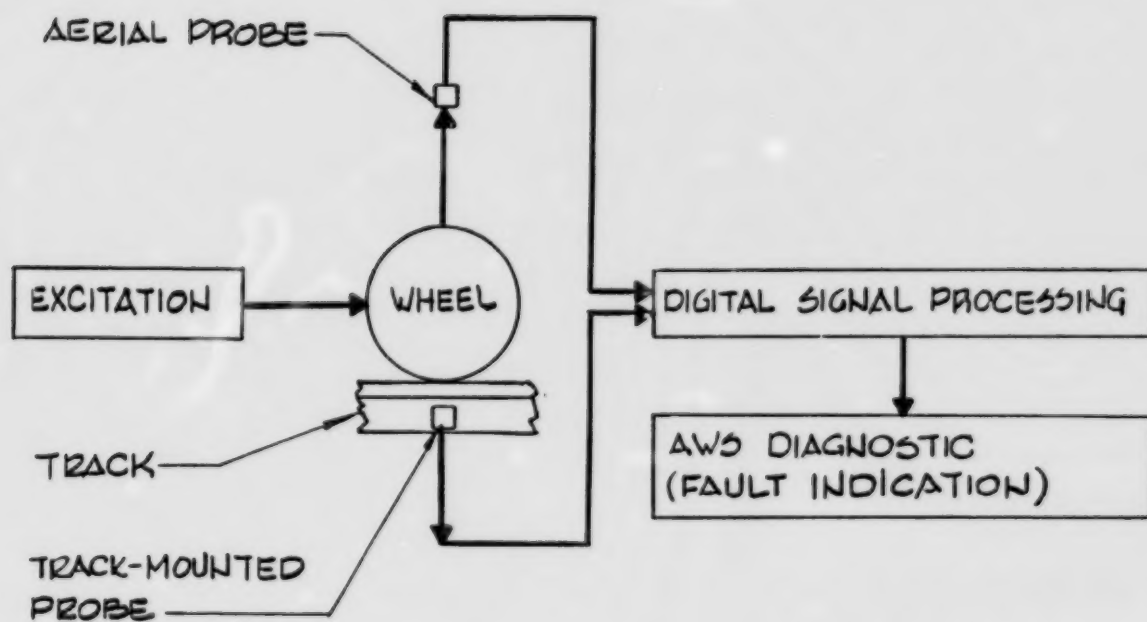


FIGURE 2.1 SCHEMATIC OF ACOUSTIC SIGNATURE INSPECTION SYSTEM COMPONENTS

2.2

Wheel Crack Detection (Cont'd)

The excitation may be based on a physical impact (hammer blow) if the system has to be excited in the audible range of frequencies or with an ultrasonic device such as an electromagnetic acoustic transducer (EMAT) or a piezoelectric (quartz crystal) transducer to increase the range of frequencies of interest.

Following the excitation, the vibratory (mechanical or electromagnetic) energy, i.e. the signature of the excited wheel, can be measured directly on the wheel using contacting (accelerometer) or non-contacting probes (laser-based accelerometer, proximeter). The signature of the wheel can also be measured using microphones to monitor the sound radiated into the air following impact.

The spectrum of a given wheel signature can then be processed by various digital signal processing techniques available directly on the analyser or programd with a micro-computer inter-connected to an analyser.

In the event that a defect is present the passage of waves within the wheel will be affected, and reflections (echoes) from the defect will be generated. By monitoring and analysing the signature it is thus possible, in principle, to know if there is a defect and its characteristics.

The final objective of data processing output should be to identify and characterize all wheel faults.

Ultrasonic Principles

Ultrasonic defect detection is potentially practical because established electrical means are available for producing and detecting vibrations in the megacycle per second region, and the defects being sought are of appropriate size for detection by the short wavelengths of ultrasonic waves. The detection is possible because the waves are reflected from a crack or other abrupt change in the elastic properties of the material in which the wave is travelling. Hence, either an echo can be detected when a crack interrupts a beam, or the ultrasonic intensity of the continuing beam will be much reduced or even zero.

Unfortunately, a characteristic of ultrasonic systems as applied to railroad wheels is that only surface or Rayleigh waves around the tread can be transmitted in a field service environment, so that only defects within a radial depth of some 1 cm of the rim surface will be detectable. A further complication is the need to maintain a good (liquid) contact between the piezoelectric

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2.2

Wheel Crack Detection (Cont'd)

crystal transducer which generates the ultrasonic input pulse and also serves as receiver.

To date, no automatic inspection system has been developed that functions within the railroad operating environment with a capacity to identify all of the defects which would be cause for condemnation of wheels against Association of American Railroads criteria.

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3.0 OBJECTIVES

3.1 Modal Objective

To enhance the performance characteristics of Canadian freight cars with regard to safety, energy efficiency, maintenance and life-cycle costs.

3.2 Modal Sub-objective

To improve safety and efficiency of car maintenance and reduce life-cycle costs by improving performance and maintenance of wheels and other critical components.

3.3 Project Objective

To evaluate the effectiveness of acoustic and vibration measurement and analysis techniques as the basis for a system capable of automatically identifying and sizing faults (cracks, shelling, etc.) in railway vehicle wheels.

3.4 Project Focus

To investigate the use of an acoustic and vibration measurement technology process known as "intensity analysis" in the identification of thermal crack and other faults in railway rolling stock wheels.

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4.0 TECHNOLOGY ASSESSMENT

4.1 Initial Survey

Within the context of the objectives of Section 3.0 of this report, a survey was conducted comprising literature review, telephone interviews, and field visits:

- to assess the need for automatic field crack detection equipment;
- to assess the status of ongoing R and D, and previous development efforts;
- to ascertain the characteristics of the defects to be identified;
- to determine the physical and performance requirements for a crack detection system;
- to assess the economic viability of an automatic crack detection system.

The survey concentrated on North American experience for freight application. Western European service is much less demanding than North American requirements, and the problems of wheel defects have not received the same degree of attention. The Federal Republic of Germany has been actively developing a field ultrasonic crack detection system to identify any tread cracks on passenger service car wheels as the trains enter selected stations. This is further discussed in Section 4.1.2. Wheels on the French (SNCF) TGV are checked ultrasonically at scheduled intervals. However, SNCF has made great efforts to identify and eliminate the causes of cracking.

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4.1.1 Literature Review

Methodology

A computerized literature survey was conducted against key words, supplemented by general requests for references to CN Rail and other sources. This initial survey was supplemented by personal contacts and visits which resulted in further recommended reading.

The resulting bibliography relevant to the proposed system is given in Appendix C, and has been divided into three groups:

- the principal papers and publications addressing wheel crack detection systems;
- the principal papers and publications addressing Cepstrum analysis for signal processing;
- the principal papers and publications addressing the characterization of wheel cracks.

Comments

Crack Detection Systems

An overview of the literature on the subject of crack detection systems for railroad wheels reveals that although extensive work has been done and is continuing, there has been no comprehensive automatic detection system developed which meets railroad industry needs.

Two leading technology contenders for automated inspection of moving wheels are reported in the literature:

- o The first method uses audio frequency response of the wheel when struck by a hammer. A major part of this work was conducted at the University of Houston.

Dousis (2.1) has presented the development of a wayside system for inspection of railroad wheels in service using acoustic signature analysis. The work was based on a laboratory demonstration system which was developed earlier. The main objectives of the study were to select a source of excitation most suitable for a flaw detection system, and to decide whether sound or mechanical vibration would be the better form of excitation.

4.1.1 Literature Review (Cont'd)

Crack Detection Systems (Cont'd)

Nagy and Finch expanded on this work with a feasibility study (2.2) on the use of acoustic signatures for detection of flaws in wheels which was conducted with the ultimate objective of developing an intrack device for moving cars. Determinations of the natural modes of vibrating wheels under various conditions are reported. Differences in acoustic signatures were found between good and cracked wheels, including spectral changes and variations in the time decay of sound. Various sounds occurring in normal railroad practice, such as rolling noise on welded rail and over joints and retarder screech, were investigated. It was concluded that special purpose impactors would have to be developed for a serviceable device. Pattern recognition techniques and a computerized processing scheme were used for identifying good and bad wheels. A laboratory demonstration system was constructed and found to be 85% reliable when system malfunctions were discounted. It was observed that while ultrasonic techniques can only find flaws within a shallow depth below the surface of the wheel tread, the acoustic technique had the potential to find flaws anywhere on the wheel tread.

In an update, Haran reports (2.3) that earlier work had established the feasibility of analysis of acoustic signature in the inspection of railroad wheels, to the extent that such a system was installed and operated on a line owned by Southern Pacific Transportation Company (commonly called Southern Pacific). The purpose was to inspect the wheels on a train as it went past an inspection site, and analyse the data in real time. The wheels on the train were sensed by magnetic wheel sensors which activated an electromechanical hammer, installed on the inside of each rail. The hammers struck the wheels on each axle, and the sound was picked up by a microphone installed in front of each hammer and transmitted to a minicomputer at a remote location via dedicated telephone lines. Previous work had established that the best detection method was a comparison of signatures from the two wheels on a common axle. Preliminary studies were performed on data obtained from a stationary test consist, specially assembled for the purposes of evaluating new algorithms. Three indicators, namely spectral cross correlation, the percentage of common peaks and a measure based on resonant frequencies, were computed from the wheel signatures. A detection rate of 45% of known defective wheels and a false-alarm rate of one invalid alarm for every three given was obtained from preliminary studies of mixed revenue service and test consist data.

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4.1.1 Literature Review (Cont'd)

Crack Detection Systems (Cont'd)

These results were fair, but more sophisticated algorithms were needed to improve on the accuracy and reliability achieved. Pattern recognition algorithms were therefore used to analyse data from test consist passages obtained from the inspection system. Various features were computed in both time and frequency domains, including the indicators mentioned earlier, and were analysed using a pattern recognition package, ISPAHAN, in which several classification schemes are available. Results from these analyses with test consist data showed a significant improvement. Specifically, a 100% detection rate was obtained using the Bayer's classifier, with a false alarm of one in eleven, when the same test consist data set was used for both training detection equipment operators and testing for identification of defects. A detection rate of 65% was obtained using the Bayer's classifier, with a false alarm of 12.5%, when different training and testing sets of test consist data were used. It was concluded that the application of pattern recognition algorithms to the test consist data produced a significant improvement in the detection rates. Suggestions for further work included incorporating the pattern recognition algorithms into the operating software of the inspection system for a period of testing.

This latter report covers the most recent work done at the University of Houston on acoustic systems. The author bases his work on the results of studies by his predecessors, and uses the acoustic signatures of the test consist to establish empirical "pattern recognition techniques" to distinguish between normal and abnormal wheels. The limited samples involved limits a generalization from the results observed.

- o The second method uses ultrasonic Rayleigh waves.

Two units by "Wheelfax" are in service at the Florida East Coast Railway. Early Wheelfax units were evaluated in 1983 by Michael (2.10). Work reported includes the evaluation of the Wheelfax concept; problems, difficulties and modifications made by purchasers of Wheelfax systems; effectiveness of this detection concept with respect to the wheel inspection criteria defined in the Field Manual of the A.A.R. Interchange Rules 1982. A cost/benefit analysis of total accidents attributed to wheel failures versus the number of these accidents where the Wheelfax may have detected the faulty wheel and, finally, recommendations on future research with

4.1.1 Literature Review (Cont'd)

Crack Detection Systems (Cont'd)

respect to the Wheelfax and other related wheel failure identification projects anticipated in the near future were provided.

No other more recent reports pertinent to the Wheelfax system were located. However, the Florida East Coast Railway installation in Miami was visited as reported in Section 4.1.3 of this report.

A more advanced prototype of an ultrasonic system by the Fraunhofer Institut has been reported by Salzburger (2.11) as in service in Germany. In this report, a technique is presented to detect surface and sub-surface cracks in the tread of railway wheels. An Electro-Magnetic Acoustic Transmitted Signal (EMATS) transducer was inserted in the rail. When the wheel contacts the transducer, it initiates an ultrasonic surface wave pulse (Rayleigh wave) of 400 kHz. This pulse propagates along the wheel tread surface in both directions making several round trips and is partially reflected by defects. An EMATS receiver unit inserted in the same rail assembly directly beside the transmitter detects, on two channels simultaneously, echoes from the clockwise and counterclockwise direction. The inspection can be done at wheels in motion at up to 10 km/h.

- o Other proposed acoustic signature systems have been suggested which rely upon on examination of the noise emanating from wheels in motion (in the absence of a specific input). None appear to have progressed due to the complexity of the problem.

No references were found where researchers had considered application of intensity analysis techniques to the wheel crack problems.

Identification and characterization of the acoustic wheel signature (AWS) has a significant role in the overall signal processing (and hence defect detection/identification) problem. A body of literature on wheel noise sources, characteristics and suppression exists (2.4-2.9 incl). Theoretical models have been developed for the vibration characteristics of a rolling wheel on a rail (2.5, 2.7, 2.9) and fairly good correlations between theory and recorded vibrations have been found. This data does not appear to have been incorporated into the signal processing techniques for acoustic data, reported in the literature.

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4.1.1 Literature Review (Cont'd)

Although magnetoacoustic stress measurement techniques do not strictly apply to crack identification, the literature was studied to ascertain whether this technique might be used since a crack will pose a local (zero stress) discontinuity in a tensile stress field. In a typical paper on this subject (2.12), uniaxial stress effects on the low-field magnetoacoustic interaction have been studied using bulk compressional waves and Rayleigh surface waves in numerous steel samples having various impurity concentrations. The results invariably showed that the initial slope of acoustic natural velocity variations, with respect to net induced magnetization parallel to the stress axis, is positive under tension and negative under compression. The results of current measurements in railroad rail steel having about 0.68 wt. percent carbon content are typical for medium-range carbon steels. The low-field natural velocity slope in this particular type of steel, which is almost zero when unstressed, becomes steeper with increased magnitude of stress in both directions. Hence, nondestructive determination of the sign of residual stress in railroad wheels and rails is possible using this techniques. This paper discusses the basic physical mechanism underlying the experimental observations and presents the results obtained in railroad rail steel. Application of the principles to identification of cracks and other defects, in the field, does not appear feasible at present.

System Economics

Only one reference (2.10) was located which addressed the question of wheel crack detection economics. The approach taken was to conduct a cost/benefit analysis:

The cost of installation of a nation-wide system for automatic crack detection, including purchase price, installation cost, and maintenance costs constituted the "cost".

The cost of derailments in the U.S. due to cracked wheels for the period 1976-1980 was assessed comprising direct costs to the railroads, costs to insurance companies, personal losses, and cost of replacing wheels. Elimination of an estimated portion of this cost by use of the automated crack detection system constituted the "benefit".

The report found the Wheelfax system in question was not viable. CP Rail reached the same conclusion for purely technical reasons. Conversely, Florida East Coast Railway found the system to be cost effective.

4.1.1 Literature Review (Cont'd)

System Economics (Cont'd)

The analysis as presented in the report has serious flaws. These included the assessed costs to insurance companies as well as personal losses, which were assumed, without substantiation at ten times the railroad costs of derailments; possible reduced labour costs with the use of an automated system were ignored; and the potential savings arising from elimination of serious derailments was not addressed. The insured party was not identified. The absence of railroad insurance in Canada is an additional factor which makes Canadian/U.S. comparisons difficult.

The analysis does focus attention on the need to develop a cost effective system if it is to be accepted for introduction to service.

Cepstrum Analysis

The cepstrum is defined as the spectrum of a logarithmic amplitude spectrum. It is an example of a non-linear filter and can be used to detect any periodic structure in the spectrum (2.14). The existence and delay times of echoes are easier to establish in the cepstrum than in the original acoustic spectrum. Furthermore, the effect of echoes is additive and signal filtering to remove them, if desired, is also easier. Cepstrum analysis is therefore an important element of the signal processing.

A number of papers have been written on cepstrum analysis and its applications (2.13-2.17 incl.). It is interesting to note that the technique has been extended by Fahmy (2.14) to wheel crack identification. Surface waves are produced by hammer impact on the rim of a railroad wheel. They travel around the wheel tread making one complete traverse of the circumference approximately every millisecond. If a receiver is located close to the impact point the signal shows a series of arrivals at millisecond intervals. If a crack is present in the surface, there will be an extra impulse received in the first millisecond interval. Both contacting accelerometers and noncontacting microphones can be used to detect the signals. If the signals are digitized and processed in time, frequency, and quefrency domains, the presence of the crack can be seen most clearly by "liftering" the cepstrum to remove all but the initial reflection from the crack.

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4.1.1 Literature Review (Cont'd)

Wheel Cracks

As with crack detection systems, an extensive literature exists on the subject of occurrence and causal factors of cracks in railroad wheels (e.g. 2.18-2.37 incl.). This body of literature addresses an understanding of the state of stress and mechanism of cracks (e.g. 2.20-2.32 incl., 2.37) and surveys of the frequency of occurrence of cracks (e.g. 2.18, 2.19, 2.36).

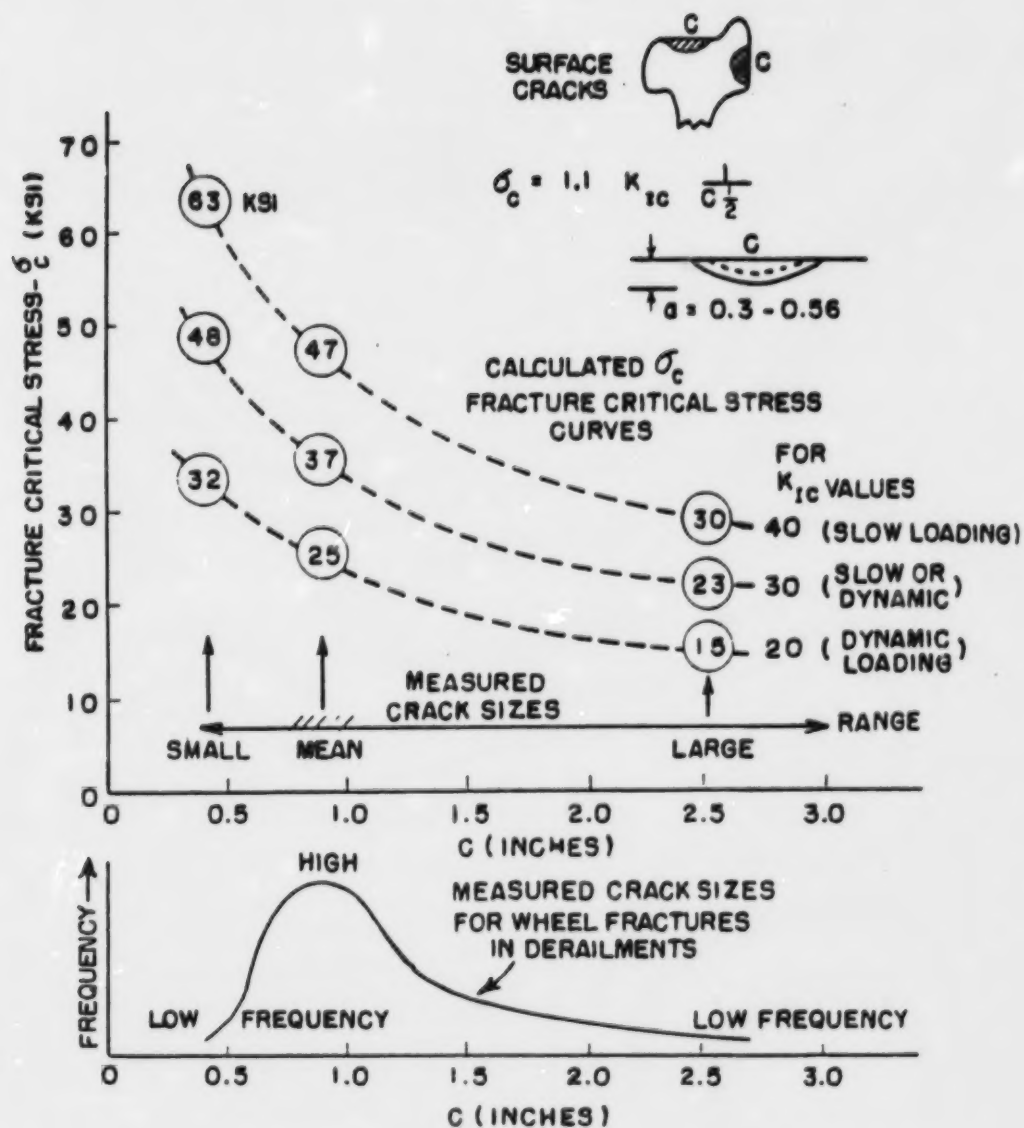
Reference number 2.36 summarizes an extensive research program into the causes of wheel thermal failure. Results of material property tests, review of failure data, dynamometer tests, roll dynamics unit, track tests, and theoretical and experimental stress analysis show that heat-treated wheels of designs which meet the requirements of A.A.R. Standard S.660 (low-stress wheels) are significantly more resistant to failure.

Volume I presents a summary of the data and results, while Volume II gives a detailed report on each of the technical tasks undertaken in the completion of the program. Volume III is an appendix of highly detailed research data.

A key factor in the assessment of intensity analysis technology application to wheel crack determination is a knowledge of the size and location of cracks to be identified and their frequency of occurrence on a single wheel. In this context, references 2.17, 2.18, and 2.36 provide the most detailed, pertinent data available.

Data taken from reference 2.36 and reproduced in Figures 4.1, 4.2, 4.3 and 4.4 shows that cracks must be identified at lengths/depths of less than $\frac{1}{4}$ " if derailments due to broken wheels are to be averted. It also shows that the majority of (but not all) catastrophic cracks occur in the rim face, face-to-tread corner, flange and, to a lesser extent, tread surface areas. CN Rail reports a somewhat different frequency of thermal crack location from Union Pacific and Santa Fe at 30% flange, 40% center rim (tread) and 30% rim edge.

Other data from reference 2.36 reproduced in Figure 4.5 shows the average number of accidents from thermally damaged wheels to be declining, but that the accident rate is seasonally dependent and the difference between summer to winter peaks is not declining. This would appear to imply that winter conditions continue to give rise to more wheel defects and to limit effective inspection, whereas in summer virtually all defective wheels are identified and removed from service.



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FIGURE 4.1 FRACTURE STRESS VS. CRITICAL CRACK SIZE FOR SURFACE CRACKS (REFERENCE FROM 2.36)

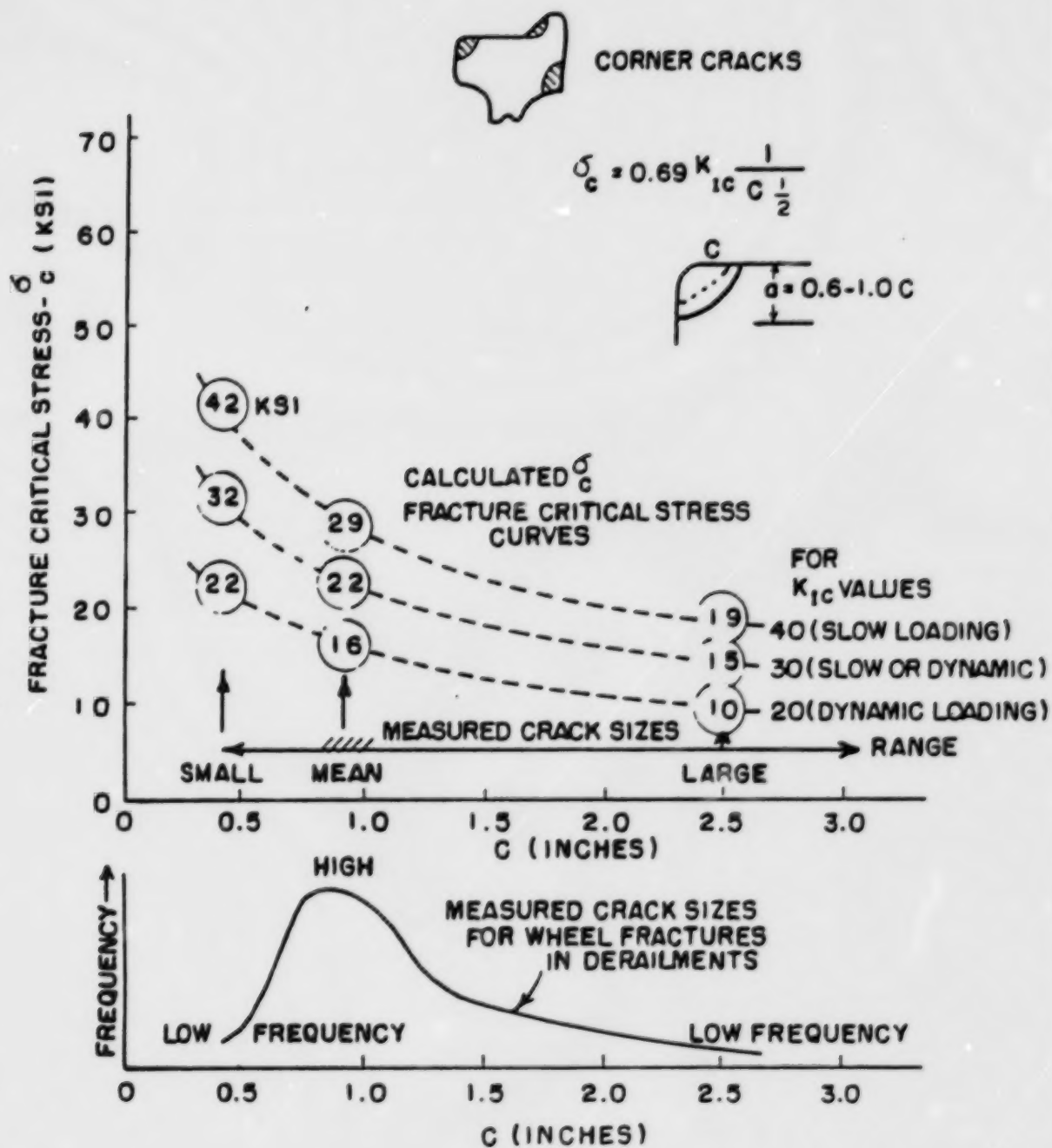


FIGURE 4.2 FRACTURE STRESS VS. CRITICAL CRACK SIZE FOR CORNER CRACKS (REFERENCE FROM 2.36)

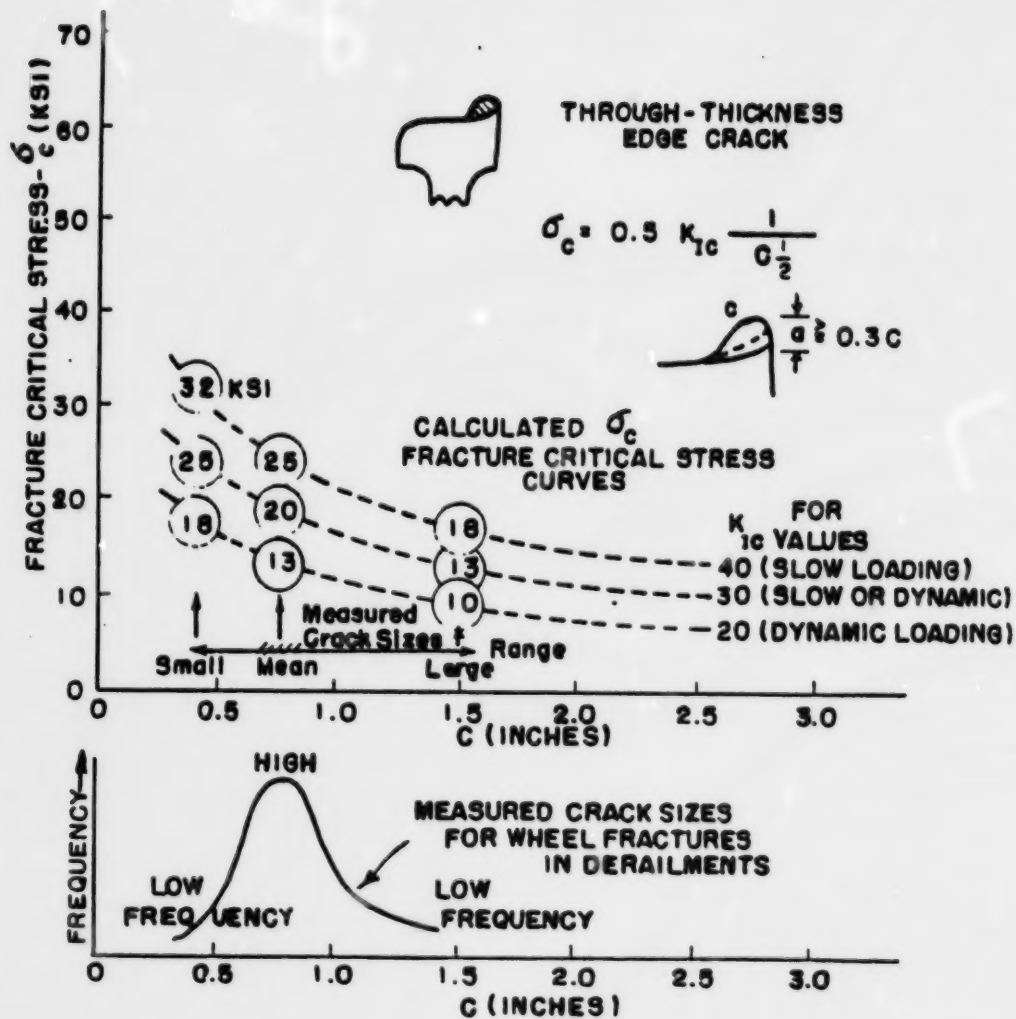


FIGURE 4.3 FRACTURE STRESS VS. CRITICAL CRACK SIZE FOR THROUGH-THICKNESS EDGE CRACKS (REFERENCE FROM 2.36)

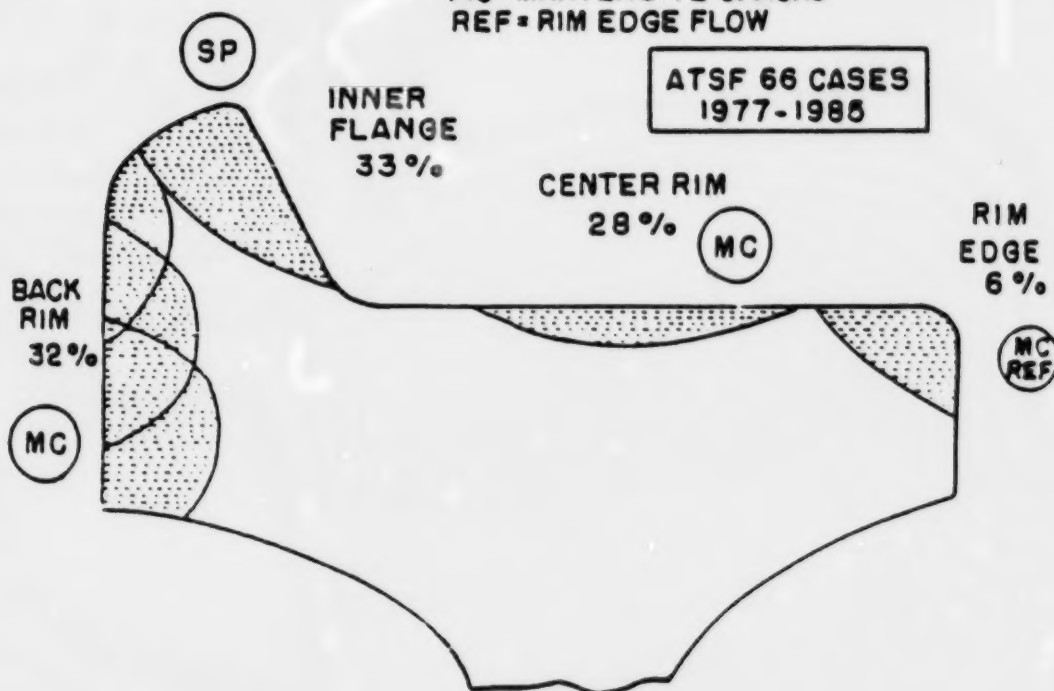
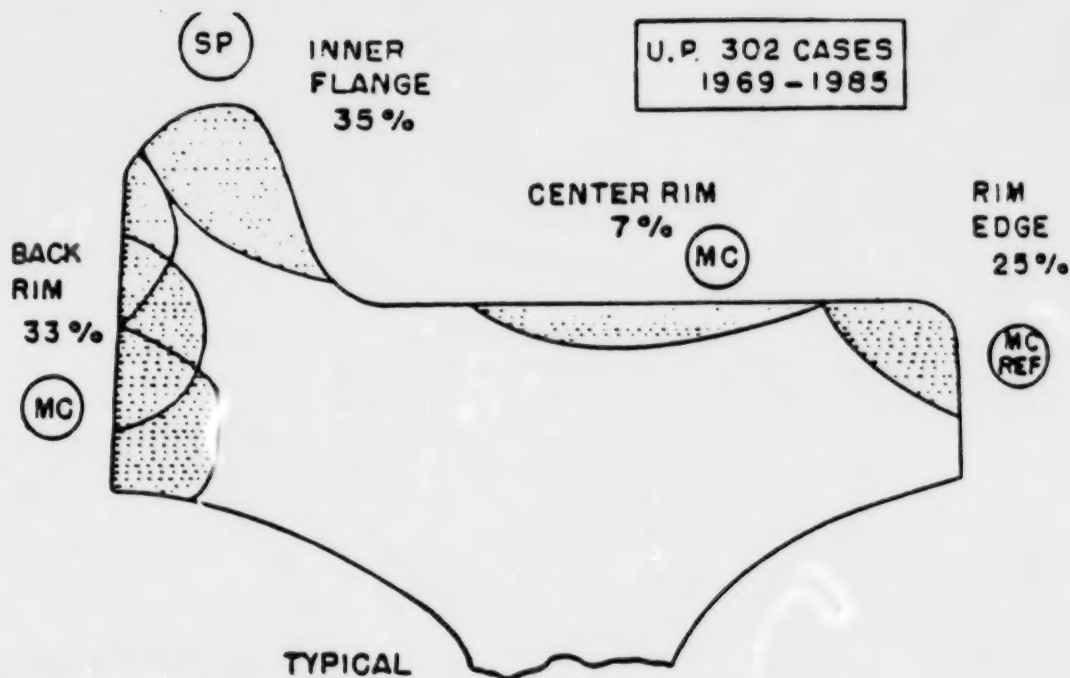


FIGURE 4.4 LOCATION AND FREQUENCY OF THERMAL CRACKS REMOVED FROM UNION PACIFIC AND SANTA FE RAILROADS (REFERENCE FROM 2.36)

CONTROL CHART
FOR THE NUMBER OF ACCIDENTS CAUSED BY THERMALLY DAMAGED WHEELS
FROM THE FRA ACCIDENT DATA BASE

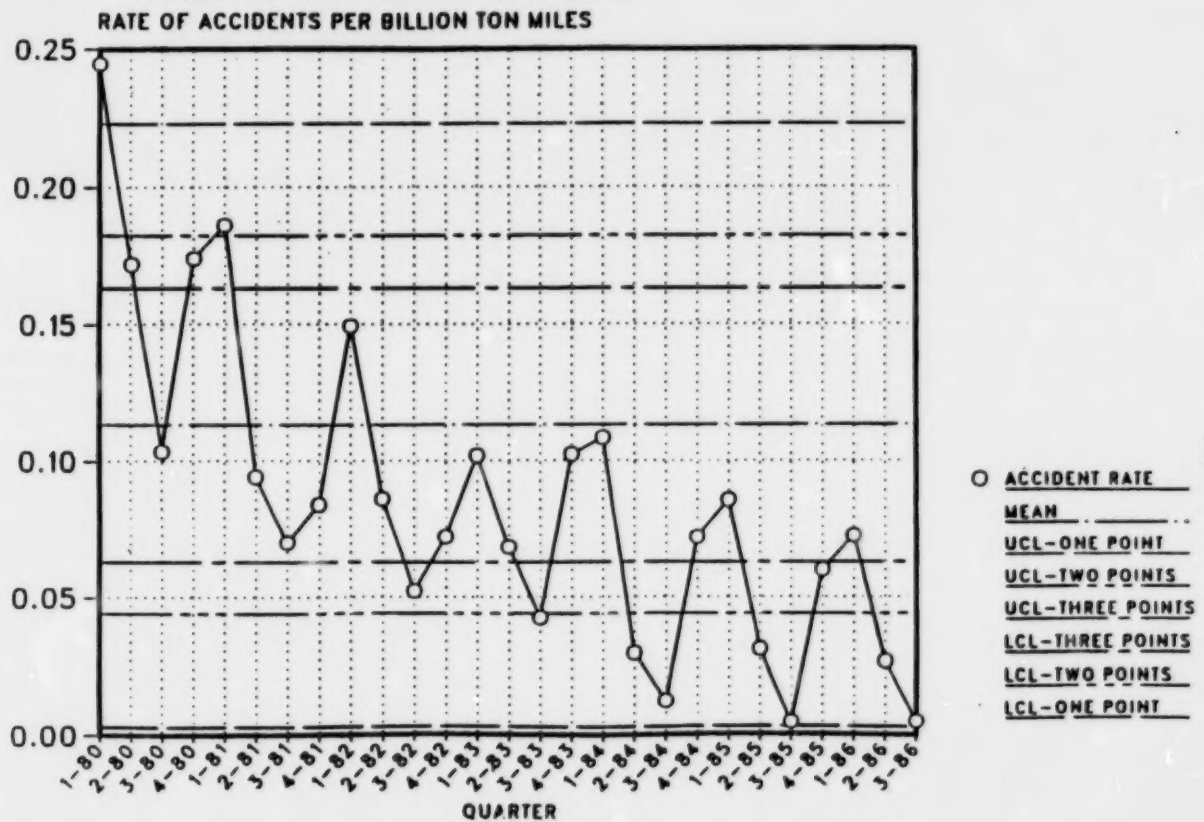


FIGURE 4.5 RATE OF ACCIDENTS PER BILLION TON MILES DUE TO THERMALLY DAMAGED WHEELS (REFERENCE FROM 2.36)

4.1.1 Literature Review (Cont'd)

Wheel Cracks (Cont'd)

A significant observation (2.37) is the discrepancy between experimentally determined conditions of residual stress which would warrant condemnation of a wheel and A.A.R. criteria for wheel rejection. Although this data is relevant to the crack problem, it is beyond the scope of a crack detection system to take all of the relevant causal factors into account.

Moore and Devlin (2.18) have conducted a detailed statistical analysis of wheel problems for Canadian coal trains. This report presents the results of a statistical study undertaken to determine those defects which contribute most to system wheel cost and also attempts to isolate the factors which contribute to such failures. The data used was obtained from the maintenance records of 100-ton gondola cars. A number of factors were considered for grouping purposes, including route travelled, type of side bearings, type of car and steerable versus non-steerable trucks. It was found that significant differences occurred in the relative incidence of particular failure types for the car groupings utilized. Also, it was shown that various factors can have significant effects on the mean mileage between wheel failures. The potential benefits of a Wheel Failure Reporting System were reviewed.

Although the focus of the report is coal trains, the study utilizes comparative data, e.g. between mountain and prairie routes, to demonstrate that shelling is essentially insensitive to route/service patterns. It is shown that shelling in coal train service far exceeds all other causes of wheel condemnation though not to the extent found in overall service, reported in Table 2 of Section 2.1. Data is presented based on service, wheel mounting (steerable/non-steerable), mileage to condemnation, and season. Overall, some 55% condemned wheels are rejected due to shelling, 15% due to thin flanges and 15% due to loose backing rings, the latter being a mode of failure outside the scope of the present study.

Conclusions reached included the observation that it was not possible with the data available to find a statistical correlation between potential causes of wheel damage and the defects observed. Furthermore it was noted that there was a very large variation in wheel life for wheels operating under essentially the same conditions.

4.1.2 Telephone Interviews and Correspondence

Interviews were conducted by telephone with selected individuals in order to assess the present status of automated wheel crack detection systems, and to determine the factors that have limited the success of previous efforts to develop such systems.

The French railways (SNCF) constituted a particular case because of the experience with the high speed T.G.V. passenger trains. For SNCF a written response was solicited.

Personnel contacted are listed in Table 4.1.

- o Both D. Stone (A.A.R.) and C. Gannett (F.R.A.) identified the need for automatic wheel crack detection and have in the past funded development efforts. In the case of the F.R.A. this work is still continuing. Follow-up visits were made. These are discussed in the next section of this report.
- o Dr. Finch of the University of Houston has published many papers on the subject of wheel crack identification and has reported development of a field-tested system. He is an acknowledged leader in the field of acoustic techniques (for wheel crack identification).

The system built and tested by Dr. Finch comprised nominally simultaneous mechanical impact of both wheels on a common axle by spring-loaded mechanical hammers. Microphones approximately 1" from the wheel outer surfaces (rim faces) monitored the acoustic signatures. The signals were processed using digital techniques to filter out noise, and the resulting spectra from each wheel were compared electronically. Any significant difference was attributed to cracks or other defects in one of the wheels, which must be subsequently inspected mechanically.

- The University of Houston conducted laboratory work and field tests to the point where field trials with a prototype field system were conducted in conjunction with Southern Pacific at the Englewood Yard in Houston.
- Equipment installed was operated and data collected under field conditions.
- As would be expected with an R&D program, changes were effected with the equipment during the test period.

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TABLE 4.1

PERSONNEL CONTACTED FOR TELEPHONE INTERVIEWS

*D. Stone -	Director, Metallurgy - Association of American Railroads, (312) 567-3580	Industry Requirements
*C. Gannett -	Project Officer - Federal Railroad Administration, (202) 366-0966,	Safety Requirements
*R. Finch -	Professor - University of Houston (713) 749-7381	Researcher (Acoustics)
G. Pennington -	General Manager, Denver X-Ray Instruments Inc. (814) 949-2035	Researcher (Radiography)
H. Hudstchen -	Scientist, Fraunhofer-Institut, Saarbrucken, F.R.G. 0681-302-3823	Researcher (Ultrasonics)
H.J. Salzburger	Project Manager, Fraunhofer- Institut, Saarbrucken, F.R.G. 0681-302-3823	Researcher (Ultrasonics)
R. Tardif -	Mechanical Superintendent, Florida East Coast Railway (904) 731-8250	User, equipt. in service
*R. Burke -	Sup. Signal & Comm. Florida East Coast Railway (904) 731-8250	User, equipt. in service
W.E. Thomford -	Former Asst. Chief Eng., Southern Pacific (415) 588-0734	User
J. Harstad -	Manager, Mech. Eng., Southern Pacific (415) 541-1410	User
*S. Ditmeyer -	Chief Engineer - Research, Burlington Northern Railroad (913) 661-4168	Potential User
W. Kucera -	Mgr. Q.A., Griffin Wheel Company (312) 346-3300	Wheel Manufacturer

* Follow-up visits conducted.

4.1.2 Telephone Interviews and Correspondence (Cont'd)

- At the end of the agreed test period, Southern Pacific decided to discontinue further work. The system had been taken to the working prototype stage but false alarms still occurred and the system had not been integrated into yard operations for use by the yard crew. The resolution of outstanding technical problems will require significant work.
- o G. Pennington of Denver X-Ray has used radiographic techniques for inspection of tank-cars to determine whether cracks were present, and has used X-ray diffraction (low intensity short wavelength X-rays) to assess the state of residual stress on the surface of railroad wheels and in journal bearings.

Most of this work has been done for Conrail, for freight applications.

Pennington believed Denver X-Ray to be at the forefront of equipment development for both crack identification and state of stress determination and competitively ahead of South West Research Institute (who use Barkhausen's method).

The wheel inspection system developed is powered by a 115V 15A outlet and a 20-30' long high-tension cable. The inspection head is small enough that it can be hand-held. The electronics weigh 150-200 lbs.

The rate of inspection is slow - 200 to 300 measurements per day, and equipment cannot make measurements on a moving wheel. Application is primarily for stressed state and can detect cracks .005" deep.

Although X-ray diffraction equipment (as distinct from radiography) is not suitable for field wheel crack detection due to slow rate and need for stationary wheels, it was noted that evolution of this equipment during the last five years has been significant, particularly in the area of equipment portability and rate of sampling.

- o Personnel of the Fraunhofer-Institut reported that they had developed an ultrasonic system for the Deutsche Bundesbahn.

The Bundesbahn anticipates introduction of passenger trains to operate at 300 km/hr maximum. Identification of wheel cracks and any possible shelling is regarded as essential for these trains. The system will monitor passenger cars, locomotives and possibly freight cars, with installations at the entrance to selected stations.

4.1.2 Telephone Interviews and Correspondence (Cont'd)

The system comprises a set of four transducers set in a "boot" in the rail which excite a wheel with a circumferential surface wave pulse. Monitoring of the reflected signal output can be used to determine presence of cracks (or not) in the rim.

The system has been installed as a prototype in service. Trains can pass at up to 20 km/hr. Servicing and maintenance were described as negligible. During one year, one transducer, only, had to be replaced. Defective wheels were identified and the yard crew notified to conduct a visual inspection. The false-alarm rate has been low.

It was claimed that the system could detect cracks in the tread and flange as small as 1 mm deep. It can differentiate between cracks (which give a sharp echo) and shelled wheels (which give a "long" signal). Plate cracks, worn treads etc. cannot be identified.

- The prototype is installed in Würzburg, near Frankfurt.
 - Two years field experience has been gained with the prototype. It is working well. The system is still being tested.
 - The system has been designed and constructed for detection of cracks on the tread surface, i.e. the rolling surface.
 - The system has detected cracks not visible to the naked eye.
 - 40 axles can be inspected, and data stored. The operator then gets the output protocol.
 - High axle loading and skidding due to braking do not pose problems.
 - Three or four production systems are planned.
- o R. Tardif observed that Florida East Coast Railway (F.E.C.R.) has long felt the need for an automated wheel inspection system. An existing ultrasonic system installed by Wheelfax in Jacksonville some 12 years ago functions to the satisfaction of F.E.C.R. and a second unit was recently installed in Miami.

The F.E.C.R. yard in Miami was subsequently visited (see Section 4.1.3).

4.1.2 Telephone Interviews and Correspondence (Cont'd)

- o W. Thomford had been a user of Dr. Finch's acoustic system while he was with Southern Pacific Railway. He made the following observations:
 - The principle of the system was to compare the acoustic spectra of two wheels on one axle. It did not identify which wheel was defective. Subsequent visual inspection was required.
 - One particular train was used with known defective wheels on some cars. Over a period of months the system always identified those wheels.
 - In principle, the system could also analyse bearings, but this was never tried.
 - The system operated for train speeds to 35 m.p.h. which was adequate.
 - Significant hardware development would still be required to achieve a marketable system.

Mr. Thomford believed Dr. Finch's approach was in the "right direction" and that with more work it could be developed to meet the railroad industry's needs. Unfortunately, funding had been terminated and he did not believe any further developments had been made.

He had also evaluated the F.E.C.R. system but observed that it only penetrated $\frac{1}{4}$ " into the wheel tread, and could not identify plate or hub cracks. Furthermore, F.E.C.R.'s rail network was much smaller and simpler than Southern Pacific's and a crack detection system suitable for F.E.C.R. was not necessarily appropriate to S.P.R.

- o J. Harstad of Southern Pacific Railway had been active in the decision not to renew funding for Dr. Finch's development work.

He was clear that the need exists for any automated device that will reduce operating costs and improve system reliability. A field wheel crack detection system fits this category exactly.

However, the development of new equipment is the function of the A.A.R. which also establishes standards and acceptance criteria.

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4.1.2 Telephone Interviews and Correspondence (Cont'd).

- o W. Kucera of Griffin Wheel had been on loan to the A.A.R. for four years to manage activities related to wheel problems in general, and to the problem of detection of wheel cracks in particular.

Key observations were:

- There is a real need for an automated crack detection system.
- Detection of any crack of (say) 1" wide by $\frac{1}{4}$ " is a "must", and any steps to automate and/or improve present inspection methods should be undertaken.
- No criteria for equipment requirements exist because there is no equipment.

He observed that Florida East Coast is a unique operation in that virtually all cars entering the system must pass over one bridge in Jacksonville. Thus, there is a single checkpoint to be monitored. Although the F.E.C.R. Wheelfax system does not detect all cracked wheels, the high level of monitoring possible with one machine radically improves the economics of the system.

He also noted that the acoustic signature of a crack in a cast wheel is not the same as the signature in a forged wheel. In the context of acoustic systems, Dr. Finch had been successful in characterizing the technique.

- o S. Ditmeyer's comments are covered by notes on a visit in Section 4.1.3 of this report.
- o The French approach to crack identification for wheels in critical service, such as the T.G.V., has been to schedule visual and ultrasonic checks at specific intervals 40 - 60,000 km.

These checks are conducted although the major emphasis has been directed to elimination of the causes of cracking at the manufacturing stage and in service.

SNCF is examining the possibility of automating operations, but this work is still in the study stage.

4.1.3 Field Visits

On the basis of the literature review and telephone interviews, field visits and presentations were organized selectively, as given in Table 4.2.

TABLE 4.2

FIELD VISITS

<u>Agency</u> (and visit date)	<u>Role</u>	<u>Contact</u>
U.S. Federal Railroad Administration (21 March 1988)	Regulatory Agency	C. Gannett Chief, Equipment and Operating practices, Safety Research Division
Association of American Railroads (24 March 1988)	Industry Association	D.H. Stone Director, Metallurgy
University of Houston (22/23 March 1988)	Research Centre - Acoustics	Dr. R. Finch Professor, Dept. of Mech. Eng.
Florida East Coast Railway (30 March 1988)	Owner and operator of only identified automatic field wheel crack detection system (Ultrasonic) in service	R. Burke Superintendent, Signal and Communication
Burlington - Northern Railroad (31 March 1988)	Major U.S. Railroad with ongoing research on wheel defects	S. Ditmeyer Chief Engineer-Research Communications and Control Systems
Fax Co. (presentation 10 May 1988)	Developer of "Wheelfax" system	J. Cowan Sr. President
Candet (Presentation 23 July 1988)	Representative of Krautkramer/Fraunhofer Institut	S. De Walle President

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4.1.3 Field Visits (Cont'd)

Federal Railroad Administration

- o The F.R.A. is supporting a comprehensive wheel safety program comprising:
 - An understanding of the state of stress of wheels.
 - Measurements of state of stress of wheels (destructive).
 - Development of non-destructive test equipment for measurement of state of stress of wheels, ultimately intended for field use, based on ultrasonics.
 - Development of non-destructive test equipment for detection of defects, principally cracks, in wheels based on ultrasonic technology, ultimately intended for field use.
 - Evaluation of wheel performance of increased capacity (125 ton) cars.
 - A 5-year performance survey of suspect wheel (Class "C") performance.

Contract work with both the National Bureau of Standards (N.B.S.) and NASA is underway.

The N.B.S. program is based on an Electro-Magnetic Acoustic Transmitted Signal (EMATS) for crack determination, and the NASA program is based on ultrasonics for stress determination. Both were reported as unsuitable for field service at present.

Critical crack size was regarded as somewhat less than $\frac{1}{4}$ ". Data collected showed that probability of wheel failure for wheels with cracks less than $\frac{1}{4}$ " was small.

The Equipment and Operating Practices Safety Research Division is interested not only in crack/defect identification but also in development of wheels less likely to develop cracks than those currently in service. In the longer term, this work should lead to fewer cracked wheels, fewer derailments due to failed wheels and a lowered interest in crack identification.

Conversely, tests are due to begin shortly at Pueblo with a new class of 125-ton capacity coal cars (38" diameter wheels), with more severe operating wheel loads than those in present service. Furthermore, although the probability of a failed wheel might be reduced, transport of inflammable materials,

4.1.3 Field Visits (Cont'd)

Federal Railroad Administration (Cont'd)

toxic substances and nuclear wastes will continue to pose hazards which dictate that all reasonable safety precautions should be taken.

Association of American Railroads

- o Dan Stone provided an outline of A.A.R. history, experience and objectives with respect to wheel crack occurrence, characterization, detection and elimination.

He observed that although many agencies and organizations have done considerable work on wheel crack detection there has historically been a lack of unified approach. However, three key observations have emerged from the work done.

- (i) The frequency of cracks is declining due in part to a better understanding of crack initiation and propagation, and development of "better" wheel technology.

Wheel design has become more sophisticated. "Low-stress" wheels are now in widespread use.

Changes in brake shoe design and materials have reduced the thermal build-up in wheels during braking, reducing the frequency of thermal cracking.

The trend to unit trains and single-service trains composed of similar cars makes for more uniform braking loads and hence reduced frequency of thermal cracking.

For energy conservation, there has been a trend to regenerative locomotive braking, again reducing braking loads.

Track quality has been improved over the last 15 years.

There are fewer cars in service:

- . Car capacity has increased.
- . Services have been rationalized and car utilization has been increased.

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4.1.3 Field Visits (Cont'd)

Association of American Railroad (Cont'd)

Conversely, it was noted that as wheel reliability has increased, the attention given by inspectors has decreased.

- (ii) Although characterized by a high false-alarm rate, the "Wheelfax" ultrasonic system demonstrated that automatic field inspection could be done.
- (iii) The need for an automated crack detection system remains.

For member railroads of the A.A.R. visual inspection currently reveals 8000 cracked wheels per year which must be removed from service. There are some 40 derailments per year due to cracked wheels that are not identified, i.e. the "miss" rate is 0.5% (or the identification rate is 99.5%). The inspection level could be as high as one check per 1000 miles travelled, and the crack propagation rate is relatively slow, though significant. The true rate of crack propagation is not thoroughly known yet. Missed cracks are attributed to crack location (back of wheel, tread crack with crack at tread-to-rail interface), poor lighting at time or location of inspection, poor weather (rain, snow or cold), or inattention by inspector due to other factors.

An automated system should be able to:

- detect cracks under adverse conditions;
- reduce inspection time/release inspectors for other duties;
- identify sub-surface cracks.

It was observed that the depth and length of cracks tend to be similar. By the time a crack achieves $\frac{1}{4}$ " length, the mechanics of the loading tend to increase the rate of crack propagation leading to a complete wheel failure. Detailed information is available in A.A.R. reports.

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4.1.3 Field Visits (Cont'd)

Association of American Railroad (Cont'd)

(iii) (Cont'd)

At present the ultrasonic technique is the best known technology although it was noted that the ultrasonic system detects tread cracks only. Only two field systems were known to exist (Florida East Coast "Wheelfax" system and Deutsche Bundesbahn/Fraunhofer Institut). Unlike North American Service, European passenger trains are subject to light loads and frequent stops which result in many small surface cracks.

A.A.R. does not intend to conduct any further R. & D. for crack detection systems at this time. A.A.R. will monitor developments and perform evaluations. Advice will be given to the member railroads. This policy has evolved in part from the failure of earlier development programs to meet expectations.

Care should be taken with respect to false alarms:

- A false alarm which necessitates a train to stop is very expensive, and highly undesirable.
- A false alarm which would focus an inspector's attention to a particular wheel where the train was scheduled to stop and the inspector was scheduled to be present for checking any suspect wheels was not viewed as such a serious problem (provided the false-alarm rate is not too high).

The A.A.R. has recently completed an in-depth study entitled "Wheel Failure Mechanisms of Railroad Cars" (Report No. R-679, November 1987). This study provides the best available data in the U.S. on mechanism of crack formation, frequency of occurrence, propagation and ultimate wheel failure.

University of Houston

Work at the University of Houston by Dr. R. Finch is believed to be the only significant research/development work done on an automatic field wheel crack detection system based on interpretation of acoustic signatures.

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4.1.3 Field Visits (Cont'd)

University of Houston (Cont'd)

A system was evolved comprising three key elements:

- . hammers to generate acoustic waves in a wheel;
- . microphones (hydrophones) to record the acoustic emissions;
- . signal processing to determine whether or not wheels were defective.

The hammer comprised a spring-loaded 2" diameter ball bearing impactor head. A train sensor activated an electric motor driven cam with retention clutch to release the spring at the appropriate time. The design impact velocity for a 1" retracted hammer-to-wheel space was 2 m/sec. The impact point was 1" above the tread at the point of contact of the wheel on the rail. One hammer assembly was located on each side of the track between the rails. The final design was the result of extensive field development work.

It was found that for environmental purposes, a hydrophone was superior to a microphone and it was located 1" from the passing wheel rim face. The impact audio output was 15-20 db above the train noise level, so that the output signal was for practical purposes "clean". The frequency range of interest was limited to below 10 kHz.

Selected signal periods were examined.

The processing comprised:

- . signal reception;
- . analog-digital conversion;
- . fast-Fourier series transform;
- . signal analysis.

The Fourier series transform comprised identification of narrow bandwidth, amplitude "spikes" corresponding to wheel natural frequency modes.

These amplitude-frequency outputs for one wheelset (2 wheels on a common axle) were then compared.

- Peaks were identified for each wheel, and for a given frequency the number of common peaks (NC) were compared, typically 5 or 6 for a selected bandwidth. The algebraic sum of the difference of peaks (SD) was computed (for a perfect match SD=0). If SD achieved a significant level it was concluded that a crack or cracks existed.

4.1.3 Field Visits (Cont'd)

University of Houston (Cont'd)

- The foregoing process was repeated for shifts in selected frequencies and bandwidths.
- The energy centre of gravity of the peaks was calculated for each wheel of a wheelset. For significant differences, there must have been a defect. The amplitude damping was calculated. Heavy damping indicated a "greased" wheel or a defect.

Problems areas identified by the University of Houston still to be resolved include:

- The false-alarm rate was reported as unacceptably high, though quantitative data was not available.
- An accelerometer on the back of the hammer would have indicated whether or not a clean impact was generated.
- Further instrumentation was required to identify discoloration on the wheel, and a contact sensor to pick up circumferential (Rayleigh) waves.
- The history of the wheels reported as defective following a defect alarm was required.

Following meetings at the University of Houston, Dr. Finch arranged a visit to the Southern Pacific Railway Englewood Yard where the acoustic system had been installed.

The equipment is no longer in operation. It was observed that there was a high probability of equipment damage, if left unprotected, due to items hanging from cars, e.g. disconnected lines, chains etc., and due to falling objects, e.g. gravel and sand in the case witnessed. However, the design had been evolved such that in large measure it met railway field equipment standards. There was relatively little evident deterioration due to the environment. Most damage appeared to have been caused by unrelated track maintenance work.

Field use of the equipment was discontinued in 1984 but the equipment appeared to be mechanically still close to operating condition with the exception of one pair of Siemens magnetic wheel detectors, and the absence of one protective cage for one hydrophone.

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4.1.3 Field Visits (Cont'd)

University of Houston (Cont'd)

It was noted that the axles on the cars could displace laterally from side to side across the track. Thus, the hammer travel to impact could vary from approximately 2" (maximum space flange to rail) to approximately 3" (flange in contact with rail). Thus, for the hammer design, the impact momentum and impact contact duration would vary from wheel to wheel. This problem would complicate signal processing.

Florida East Coast Railway

The Florida East Coast Railway (F.E.C.) has had a Wheelfax ultrasonic field wheel crack detection system in operation in Jacksonville for some 10 years. The system has been reported in the literature (10) as prone to high false-alarm rates. F.E.C. earlier invested some two years of effort by their signal and communication group to bring their Wheelfax system up to a reliable satisfactory standard (no pertinent reports were identified).

F.E.C. has recently obtained a second Wheelfax unit and installed it at the entrance to the Highleah Yard. This second system has some significant technical advances over the older Jacksonville system and is still being commissioned for service.

The overall system comprises four elements:

- the track equipment installation including signal input and recorder;
- the track-side electronics equipment for signal conditioning and analysis;
- a trackside video system for car identification;
- an office output system (connected by fibre optics to the track-side electronics output) providing printed listing of defective wheels and cars by location within the train and video output of the defective cars showing car identification.

4.1.3 Field Visits (Cont'd)

Florida East Coast Railway (Cont'd)

The track equipment comprises a liquid-filled "boot" with two transducers inserted into the track. The system is activated by magnetic wheel detectors at the approach of an axle set. At the passage of a wheel, a pressure switch within the boot activates one of two transducers which generates a circumferential 400 kHz surface wave in the wheel. This wave is received by the second transducer if the wheel is good, or reflected in some measure back to the first transducer if a defect is present. Subject to the speed of the train (up to 25-30 mph), there can be typically 10 signals passed into a single wheel as redundant checks.

The boot is made of a flexible plastic material. The boot requires replacement every 2-4 weeks. However, this requirement was recognized in the design by the provision of an easy means of replacing the plastic element.

Ancillary equipment included:

- (i) a compressed-air activated water spray onto the wheel to ensure good acoustic contact between boot and wheel. (The water also contains a cleaning agent, and an unknown "wetting" agent);
- (ii) flange guides to ensure contact of the flanges against the rail head, thereby ensuring that the tread is centred over the boot;
- (iii) coupled with (ii) above, there has been a local narrowing of the gauge by $\frac{1}{4}$ " to ensure reliable wheel location. (These details effectively resolved the hammer travel problem reported for Dr. Finch's acoustic system);
- (iv) a set of 4 magnetic wheel detectors on each side of the track to initiate measurement, and monitor wheel passage.

Systems are installed on both sides of the track some 50'-60' apart.

The track-side electronics are housed in a 10' x 10' air-conditioned cabin, together with the air compressor, liquid reservoir and a local P.C. terminal for system maintenance checkout.

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4.1.3 Field Visits (Cont'd)

Florida East Coast Railway (Cont'd)

The electronic system combined the magnetic wheelset data and the ultrasonic signal data to report the time of passage of the train, direction, number of cars, cars which had defective wheels, which axle was defective on the car, and on which side the defective wheel was to be found. In the event no data was recorded, this was reported. Good wheels were not reported.

The form of defects were not identified.

The video system was triggered by the approaching train.

A lighting system had been installed to facilitate night use.

The office output comprised a printout giving train time, direction, speed, and any defective wheel location on the pertinent car.

Cars were identified by location within the train, with the locomotive identified as number 1. (The software can differentiate between 2-axle and 3-axle bogies to avoid confusing outputs).

The video was in the form of a V.C.R. record. Playback included time of day, time from start of train passage, train speed and car location within the train. Thus, the video can be correlated with the printout. The video can be stopped for each car and a printout provided so that the defective car can be easily recognized for future inspection.

The system has a 1 microsecond input and surveys at 1 microsecond intervals. The alarm can be adjusted to trigger at an appropriate loss of signal strength at say 4, 8, 12, etc., db below input. Thus, cracks can be identified at various depths from say .060" deep by $\frac{1}{4}$ " width upwards. A setting for $\frac{1}{4}$ " to $\frac{3}{8}$ " characteristic crack dimension has been found most appropriate.

Cracks can be located from about $\frac{1}{4}$ " over the back of the flange, over the flange and tread and to $\frac{1}{4}$ " to $\frac{3}{8}$ " on the rim face. Cracks have been found up to $\frac{3}{8}$ " below the surface.

400 kHz has been found to be the most appropriate frequency.

At present, the policy for application of data output is under review.

SNC

4.1.3 Field Visits (Cont'd)

Florida East Coast Railway (Cont'd)

Crack growth is sufficiently slow that a defective wheel can be left in service. If the same car shows a repeated alarm at subsequent checks, it is assumed that the defect is serious and the wheel is given a special inspection visually and with a portable (Wheelfax junior) ultrasonic detection system. Methods for this data correlation (repeat warnings) have not yet been fully evolved.

A number of limitations to the system were noted:

- The system will only detect tread cracks. Some flange defect conditions are identified, but some located visually were not identified by the device.
- The system does not work in the case of dragging brakes.
- The rate of "no-data" signals rises rapidly as speeds exceed 20-25 mph.
- The wear rate on boots is high.
- The wear rate on the inner guide rail at the boot station is high.

A rail impact sensor installation was also visited. This facility also provides a yard office output for correlation with the wheel defect sensor.

Burlington-Northern

Burlington-Northern (B-N) traced their approach to wheel problems to the first field tests with the Wheelfax system in 1980. It was observed that the Wheelfax machines were able to detect cracks but not to differentiate between cracks acceptable or condemnable against A.A.R. standards. Since Wheelfax could identify sub-surface cracks for which no A.A.R. standards existed and which (in the case of non-B-N cars) could not therefore be condemned, serious problems existed.

For this and other reasons B-N therefore focussed their attention on determining of the state of stress in wheels. Their approach has been to support work at S.W.R.I. using the Barkhausen noise analysis technique. Correlation between Barkhausen forecast results and saw-cutting has been done in a laboratory environment and good correlation of results found. It has been determined

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4.1.3 Field Visits (Cont'd)

Burlington-Northern (Cont'd)

that the A.A.R. criteria for condemnation of discolored wheels may be suspect. The laboratory equipment used to date, which must clamp onto wheels, is not suitable for field use at present.

B-N tabled a South West Research Institute (S.W.R.I.) contractor report (2.37) which identified "safe" and "unsafe" states of stress. This data implies that for the classes of wheels examined, a true measure of acceptance or rejection of a cracked wheel should take into account the state of stress as well, or there should be some relation to the rate of crack propagation and frequency of inspection. Unfortunately, such data is not available. B-N is presently trying to establish a statistical data base.

B-N has a derailment task force. Crack detection is treated as an integral part of defect identification and correction together with hot box detection, rail impacting, etc. As automatic equipment for any of these functions becomes available, economic analyses are conducted, and decisions based on the estimated payback are made.

It was felt that for all new products, work should start with a "work duty assessment" i.e. how do the car men and inspectors conduct their work? In what form do they want data? And what duty cycle must the equipment respect? It was observed that in addition to problems of winter manual inspection (reported by D. Stone of the A.A.R.) there is a propensity of wheels to build up ice during the winter, making visual inspection more difficult.

Presentations

Presentations to T.D.C., CN Rail, CP Rail and SNC were organized to be given by Fax Co. and Candet Inc. for the two automatic crack detection systems developed and presently in service. Candet is the Canadian representative for Krautkramer GmbH licensee of the Fraunhofer system.

Wheelfax

John Cowan, president of Fax Co. elaborated on the description of the Wheelfax system (described earlier, and installed at Florida East Coast Railway).

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4.1.3 Field Visits (Cont'd)

Wheelfax (Cont'd)

A brief overview of the mechanism of thermal crack occurrence in wheels in service and the Wheelfax in-rail system for their detection was given.

The system has been under development since first field demonstrations were made over 14 years ago.

Due largely to advances in electronics, principle improvements have been:

- . computerization of the system;
- . elimination of calibration requirements;
- . increased signal strength into the wheel.

Improvements have also been made to the physical equipment/system.

Cracks can be detected down to 3/32" x 1/2" in the wheel rim, outer face, tread and flange.

The in-rail "boot" is maintained close to 100°F, filled with water/ethylene glycol. Accordingly, the system is insensitive to rail ambient temperature.

The washing system keeps the boot clean and relatively insensitive to sand box use.

In the event of a bag burst, the bag can be replaced in under 15 minutes at a cost of under US\$50. The life of a boot is up to five weeks at 8000 wheels/day.

A brief description and table-top demonstration of the Wheelfax junior portable/system was also given.

These units are simple to use, require only one day's training, and over 100 units have been sold. The unit exhibited gave more output data than CN would normally require.

A shop demonstration of the Wheelfax junior system was given at CN's Point St-Charles Wheel Shop.

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4.1.3 Field Visits (Cont'd)

Candet

Mr. S. De Walle of Candet gave a presentation on the principles and operation of the Fraunhofer automatic in-field railroad wheel crack detection system. A paper by H.J. Salzburger et al. was tabled.

- . The Deutsch Bundesbahn system comprises an electromagnetic ultrasonic frequency (430 kHz) transducer excitation/sensing system (EMATS) installed in the rail. A prototype system installed near Frankfurt has been in operation for some two years.
- . The original principle was established by inverting an ultrasonic car-mounted rail crack inspection device, transferring the inspection head and recording equipment from the car to the rail and a wayside station.
- . The main problem for automatic wheel crack detection is to establish and demonstrate reliability (i) of the ability of the system to detect all pertinent cracks and shells, and only cracks and shells (i.e. no false alarms), and (ii) of the equipment itself.
- . Initial work by the Fraunhofer-Institut addressed the question of reliable crack detection. The advantages of selecting of the EMATS system are that for the cases (a) with a gap between the wheel and transducer, (b) with dry contact between the wheel and transducer, and (c) with wet contact between the wheel and transducer, all the signals are virtually the same. This would not be the case for conventional transducers, and thus a significant cause of false alarms has been removed. The attenuation with circumferential distance has been shown to be relatively small. The "dead" zone close to the input sign is eliminated by using two sequenced EMATS. Again, this has not been done in conventional transducer systems, leaving the possibility for undetected cracks in service.

Finally, evaluation of signal strength versus crack depth in the wheel tread has shown that cracks down to less than 1 mm can be detected. Thus, a system has been developed which is potentially more reliable for crack detection than others tested.

4.1.4 Canadian Railroad Experience

To focus the objectives of the initial survey with respect to the Canadian railroads, the structured literature survey, telephone interviews and field visits were supplemented by informal discussions and exchanges of information principally with representatives of CN Rail, CP Rail and the Transportation Development Centre.

Canadian railroad experience characterized by CN Rail, CP Rail and BC Rail is similar to U.S. experience. These companies are members of the A.A.R. and respect continent-wide standards. However, Canadian experience differs in a number of facets, typically characterized by the relatively high safety record compared to U.S. counterparts. A.A.R. data for 1986 shows the number of accidents caused by thermally damaged wheels overall to be approximately 0.04 per billion ton miles. The comparable Canadian rate is less than 0.02 accidents per billion ton-miles.

Limited sample data on Canadian experience is given in Section 2.0, and further data is reported in the literature review.

Past Canadian experience with automatic field crack detection has been limited to one installation by CP Rail.

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Defect Detection Equipment Experience - CP Rail

In late-1976, CP Rail purchased and installed in the St. Luc Yard (Montreal) a Wheelfax system (i.e. an experimental automatic wayside device to detect thermal cracks in railway wheels) for evaluation. The Mechanical Department conducted this evaluation program until early-1979. Significant modifications were made to the original unit during this period to improve performance. In particular, heaters were added to improve winter operation of a paint system used to mark suspect wheels, an overspeed detector was installed to reduce the high number of false alarms occurring at speeds greater than 20 mph and a "calamity" alarm was added to identify cracks extending into the plate. The system operated continuously early in the test program and generated an unacceptable number of false alarms and operating delays. It was operated only intermittently later in the test program. By early-1979, the system was able to detect cracked wheels but could not distinguish cracked wheels from shelled wheels. The Research Department was to have assumed responsibility for the final development of the Wheelfax unit in mid-1979 but government support was discontinued. CP Rail then discontinued work on this program.

4.1.4 Canadian Railroad Experience (Cont'd)

Defect Detection Equipment Experience (Cont'd)

The Wheelfax test program did not result in the establishment of specific criteria for an in-track wheel crack detection system. In general, CP Rail would require that such a system be able to distinguish cracked wheels from shelled wheels and shelled wheels with cracks.

The Wheelfax system was located on the main entrance track to the receiving yard in St. Luc Yard. A readout strip chart recorder was originally located in the receiving yard office and later in the Car Department Planner's office, and provided an immediate permanent record of wheels tested and alarms. The responsible officer would then radio yard personnel to switch the suspect car onto the bad order track. There was no significant delay between crack "detection" and yard crew notification. Suspect wheels were subsequently examined by the Engineer of Tests to determine whether the alarm was justified.

An acceptable level of false alarms was never established.

The purpose of the Wheelfax unit was to detect thermal cracks; these are usually found on the flange tip or the tread surface towards the front rim face, and are the most common cracks responsible for the changing-out of wheels in CP service. Modifications to the Wheelfax by CP included addition of an audible alarm to alert maintenance personnel in the event of detection of a severe crack.

There was no limiting field equipment maintenance interval.

Winter operation differed from summer operation in the following ways:

- snow plows caused significant equipment damage;
- intermittent operation led to freezing (and poor performance) of the oil system used to ensure a good wheel-to-rail contact and the paint system used to mark "defective" wheels.

The performance of the Wheelfax system improved during the test program, primarily because of the heating system and overspeed detector modifications made by CP Rail. It is difficult to assess whether the maintenance record of the Wheelfax unit improved with experience by CP personnel because of the

4.1.4 Canadian Railroad Experience (Cont'd)

Defect Detection Equipment Experience (Cont'd)

significant, concurrent modifications described above. System contamination by sand from locomotives was a problem throughout the test program, however, and resulted in excessive maintenance costs.

The maximum yard speed is 15 mph.

Problems with the Wheelfax system were primarily due to the unsuitability of the original system to the Canadian railway environment.

The Wheelfax unit could detect thermal cracks, shells and through-rim cracks. The system could not, however, consistently distinguish thermal cracks and shells.

Defect Detection Equipment Experience - CN Rail

In an attempt to address problems with shelling and flats, CN Rail experimented with microphones between the rails and strain gauging rails. Although the literature reports that microphones are practical, CN Rail did not find this to be the case. However, strain gauging was found to be viable.

Incidence of Wheel Cracks

Sample U.S. (A.A.R.) data taken from reference 2.36 has been given in Figures 4.4 and 4.5. Figure 4.4 provides comparative data for the Union Pacific and Santa Fe railroads on the location and frequency of thermal cracks; data on much less frequent plate cracks is not given. Figure 4.5 shows the rate of accidents per billion ton-miles due to thermally damaged wheels over a 6-year period.

This data shows a steady decline in the incidence of accidents due to improvements in braking practice, wheel design, track quality, and train operation (as reported in visit to A.A.R., Section 4.1.3). However, the seasonal fluctuation due to a higher propensity for accidents to occur and reduced inspection quality during winter conditions remains virtually unchanged.

Sample Canadian data on frequency of crack occurrence has been given in Section 2, though extensive and fully comparable data is not available.

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4.1.4 Canadian Railroad Experience (Cont'd)

Incidence of Wheel Cracks (Cont'd)

A survey of accidents in Canada for 1985 taken from National Transportation Agency of Canada data is given in Table 4.3 showing a total of 275 derailments. The breakdown of Table 4.4 shows that of these derailments, 68 were equipment-related.

Table 4.5, giving a further breakdown, identifies 10 derailments due to wheel failure. Derailments for the period 1983-1987 are summarized in Table 4.6.

In the case of B.C. Rail, its entire fleet is now equipped with curved plate wheels, and derailments due to cracked wheels have declined to virtually zero.

It is interesting to note that although the frequency of derailments in Canada is only about half the rate reported by the A.A.R., the number of derailments due to cracked wheels as a percentage of condemned wheels is similar, at approximately 0.5%.

TABLE 4.3

ACCIDENTS 1985

<u>RAILWAY</u>	<u>NUMBER (%)</u> <u>ACCIDENTS</u>	<u>NUMBER</u> <u>FATALITIES</u>	<u>NUMBER</u> <u>INJURIES</u>
Grade Crossings	600 (39.6)	58	336
Employees Getting on and off Rolling Stock	396 (26.1)	---	396
Rolling Stock Derailments	275 (18.1)	1	22
Rolling Stock, Collisions	72 (4.8)	---	49
Maintenance Equipment Derailments & Collisions	38 (2.5)	2	50
Employees Struck by Rolling Stock	27 (1.8)	3	24
Trespassers Struck by Rolling Stock	107 (7.1)	60	47
	<u>1,515 (100)</u>	<u>124</u>	<u>924</u>

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TABLE 4.4

DERAILMENTS - 1985

	<u>NUMBER</u>	<u>%</u>
Track-related	96	34.9
Equipment-related	68	24.7
Operations-related	49	17.8
Other	39	14.2
Undetermined	23	8.4
TOTAL	275	100

Main Track	171
Yard Track	104
TOTAL	275

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TABLE 4.5

EQUIPMENT-RELATED DERAILMENTS

	<u>1981</u>	<u>1985</u>
Loose Wheels	2	2
Broken Wheels	9	10
Broken Axles	4	3
Journal Failures - Roller Bearings	21	19
Journal Failures - Friction Bearings	32	7
Truck Component Defect	12	9
Brake Gear Defective or Dragging	6	11
Draft Gear Failure	7	2
Other Rolling Stock Defects	9	5
	—	—
TOTAL EQUIPMENT-RELATED	102	68
Combination - Track, Equip., Operational	18	15
Undetermined	3	23

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TABLE 4.6: DERAILMENTS DUE TO BROKEN WHEELS (1983-1987)*

MONTH RLY TRAIN BROKEN WHEEL (PART)		DERAILED		CONSIST		REMARKS	PROPERTY DAMAGE
TYPE		UNITS CARS		UNITS CARS			
** YEAR 1983							
JAN	CP FRT	BROKEN WHEEL PLATE	0	1	3	27 PRIOR FLAW	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEEL TREAD	0	1	4	39 THERMAL SELLING (UNIT COAL TRAIN)	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEEL	0	2	5	120 (EMPTY UNIT SULPHUR TRAIN)	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEEL PLATE	0	1	3	104 (UNIT POTASH TRAIN)	LESS THAN \$100,000
FEB	CN FRT	BROKEN WHEEL FLANGE	0	14	2	101	\$100,000- \$250,000
MAY	CN FRT	BROKEN WHEEL	0	1	3	99 25% FLAW	LESS THAN \$100,000
MAY	CN FRT	BROKEN WHEEL FLANGE	9	2	4	100 THERMAL DAMAGE	LESS THAN \$100,000
JUN	CN FRT	BROKEN WHEEL RIM	0	1	3	137 PROGRESSIVE FRACTURE	LESS THAN \$100,000
SEPT	CN FRT	BROKEN WHEEL	0	1	8	120 OVERHEATING	LESS THAN \$100,000
DEC	CP FRT	BROKEN WHEEL RIM	1	0	4	45 FLAW @ HUB FILLET	LESS THAN \$100,000
** YEAR 1984							
JAN	CP FRT	BROKEN WHEEL	0	1	4	112 DEEP TREAD SELLING, PROPAGATION OF FATIGUE FRACTURE	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEELS	1	0	3	70 7/8" DIFF. IN RIMS, THERMAL DAMAGE	LESS THAN \$100,000
FEB	CP FRT	BROKEN WHEEL RIM	0	1	4	80 WHEEL DISINTEGRATED BEFORE FAILURE	LESS THAN \$100,000
MAR	CN FRT	BROKEN WHEEL RIM	0	3	3	100 THERMAL SELLING, FATIGUE CRACK PROPAGATION	LESS THAN \$100,000
MAY	CP FRT	BROKEN WHEEL RIM	0	1	3	78 PRIOR THERMAL DAMAGE	LESS THAN \$100,000
SEP	CP FRT	BROKEN WHEEL	0	1	3	79 60% PRIOR FLAW	LESS THAN \$100,000
NOV	CN FRT	BROKEN WHEEL RIM	0	1	8	79 THERMAL CRACK DUE BRAKE GEAR DEFECT	LESS THAN \$100,000
DEC	CP FRT	BROKEN WHEEL FLANGE	0	2	3	111 INTERIOR FLAW	LESS THAN \$100,000
DEC	CN FRT	BROKEN WHEEL	0	1	2	50	\$250,000- \$500,000
** YEAR 1985							
JAN	CP FRT	BROKEN WHEEL FLANGE	0	1	1	89 IMPACT DAMAGE	LESS THAN \$100,000
JAN	CP FRT	BROKEN WHEEL	0	1	2	82 POSSIBLE IMPACT DAMAGE	LESS THAN \$100,000
FEB	CN FRT	BROKEN WHEEL RIM	0	1	2	93 WHEELSET FOULED GRADE CROSSING	LESS THAN \$100,000
MAR	CP FRT	BROKEN WHEEL	1	0	4	98 PRIOR DEFECT	LESS THAN \$100,000
MAR	CN FRT	BROKEN WHEEL TREAD & FLANGE	0	1	3	87 WHEEL DISINTEGRATED	\$100,000- \$250,000
JUN	CN FRT	BROKEN WHEEL	0	1	3	101 25% PRIOR DEFECT	LESS THAN \$100,000
SEP	CP FRT	BROKEN WHEEL	0	1	4	77 PRIOR FLAWS	LESS THAN \$100,000
SEPT	CN FRT	BROKEN WHEEL	0	0	4	86 ENTERING YARD @ TURNOUT	LESS THAN \$100,000
NOV	CP PSR	BROKEN WHEEL RIM	0	1	2	9	LESS THAN \$100,000
NOV	CP FRT	BROKEN WHEEL TREAD	1	0	1	33 -27 DEG. C AMBIENT TEMP.	LESS THAN \$100,000
DEC	CP FRT	BROKEN WHEEL PLATE	1	0	3	80 PRIOR 13" DEFECT, -10 DEG. C	\$100,000- \$250,000
** YEAR 1986							
JAN	CP FRT	BROKEN WHEEL RIM	0	1	6	77	LESS THAN \$100,000
JAN	CP PSR	BROKEN WHEEL HUB	0	1	2	9	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEEL RIM	0	1	2	90 -15 DEG. C	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEEL HUB	0	1	2	93 BROKEN HUB CAUSED LOOSE WHEEL - LATER FOULED SWITCH	LESS THAN \$100,000
FEB	CN PSR	BROKEN WHEEL HUB	0	1	2	13 BRAKE DEFECT CAUSED THERMAL CRACKING, WHEEL LOOSENING	LESS THAN \$100,000
FEB	CP FRT	BROKEN WHEEL	3	15	3	39 -28 DEG. C AMBIENT TEMP. (UNIT SULPHURIC ACID TRAIN)	OVER \$500,000
FEB	CN FRT	BROKEN WHEEL TREAD TO HUB	0	20	2	87 THERMAL DAMAGE	OVER \$500,000
MAR	CP FRT	BROKEN WHEEL PLATE	0	10	4	74 36% PRIOR FRACTURE	\$250,000- \$500,000
APR	CP FRT	BROKEN WHEEL TREAD	0	1	2	50 10" PRIOR DEFECT	LESS THAN \$100,000
JUL	CN WKK	BROKEN WHEEL	1	0	0		LESS THAN \$100,000
SEP	CN FRT	BROKEN WHEEL	1	0	3	76	\$100,000- \$250,000
DEC	CN FRT	BROKEN WHEEL	0	1	3	77	LESS THAN \$100,000
** YEAR 1987							
JAN	CN PSR	BROKEN WHEEL	3	1	2	11 THERMAL SELLING	LESS THAN \$100,000
JAN	CN FRT	BROKEN WHEEL	3	1	3	75	LESS THAN \$100,000
FEB	CN FRT	BROKEN WHEEL	0	2	3	31	LESS THAN \$100,000
FEB	CN WKK	BROKEN WHEEL FLANGE	0	2	2	38 FLANGE CONNECTION FRIED SWITCH	LESS THAN \$100,000
MAR	CN FRT	BROKEN WHEEL	3	1	3	110	\$100,000- \$250,000
JUL	CN FRT	BROKEN TRAIN	1	9	4	10	\$100,000- \$250,000
SEP	CN FRT	BROKEN WHEEL	0	1	3		LESS THAN \$100,000

* SOURCE: NATIONAL TRANSPORTATION AGENCY RECORDS.

4.1.5 Commentary

Although the need for an automated crack-detection system exists, and systems have been developed, there has been to date no criteria established either for the equipment or for its performance.

In general:

- the system must require minimum maintenance;
- the performance must be sufficiently reliable and accurate to permit current inspection procedures to be discontinued;
- reliability must be significantly improved over the present visual inspection level of 96% cracked wheels identified;
- an inspection frequency of approximately once every 1000 miles would be required so that a small undetected crack could not propagate to failure before the next inspection;
- the system must be compatible with standard railroad hardware and be suitable for eventual integration into a comprehensive train inspection system;
- it must work in all environments and be able to inspect wheels at train speeds of at least 20 km/hr;
- the delay between wheel inspection and defect identification must be "short" in order that action can be taken to withdraw the suspect car from service.

Only two technologies for crack determination would appear to be potentially applicable for field use: acoustics and ultrasonics.

Limitations on the success of previous efforts have been identified:

For acoustic systems, the problems of (i) signal noise contamination and (ii) signal correlation with specific defect types, have not been resolved by researchers to date. These problems are manifested as a high false-alarm rate, and possible failure to detect defective wheels since at a first level of signal analysis, detection of small (e.g. $\frac{1}{16}$ " cracks) by "long" acoustic frequency waves is difficult.

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4.1.5 Commentary (Cont'd)

For ultrasonic systems, the state of development of practical systems is more advanced than for acoustic systems, but the technology can only address outer rim defects. The Wheelfax system still has a significant false-alarm rate and requires significant maintenance. Suitability of the Bundesbahn system to all weather environments existing in Canada and to high freight axle loadings has not been determined. The system is still in the late stages of development.

Defect accept/reject criteria have not yet been firmly established for any vibration analysis technology. The capability of automated equipment to detect sub-surface defects and crack depths must be correlated with A.A.R. standards and practice.

A review of the state of acoustic systems development showed that a number of actions could be taken to improve the state of development:

- utilize an electronically controlled impactor, or EMATS, instead of mechanical excitation (as used by others) to generate a "cleaner" input signal and increase the range of possible input frequencies;
- increase the input frequency range of the exciter to 25-100 kHz in order to improve the potential detectability of small defects and increase the vibration amplitude of surface waves;
- adapt contacting probes (accelerometers, acoustic emission transducers) or use non-contacting probes like laser accelerometers or other such devices as an alternative to traditional microphones/hydrophones;
- use intensimetry and/or simple acoustic spectra analysis;
- address signal processing as a key area for improvements.

Given the limitations and advantages of acoustic and ultrasonic systems, it is possible that an ultimate defect detection system would incorporate both technologies.

The definition of defects remains an unresolved problem. A.A.R. criteria are based on visual identification and involve a measure of subjective judgement. They are, however, the only criteria presently usable for inter-company purposes, e.g. where one

4.1.5 Commentary (Cont'd)

company takes another company's car out of service. Data from derailment investigations shows that there have been no derailments due to failed wheels, originating from a crack of 0.4" or less. Thus, a crack depth of $\frac{1}{4}$ " would appear to be a conservative, though somewhat arbitrary, criteria for wheel rejection. However, this does not necessarily coincide with A.A.R. criteria (since the depth cannot be seen), and it does not follow that because derailments occur due to $\frac{1}{4}$ " or greater cracks, all cracks greater than $\frac{1}{4}$ " result in derailments.

The rate of crack propagation under operating conditions is in general not known, and overheated (discolored) wheels with tensile residual stresses will propagate cracks faster than new wheels with compressive residual stresses. Furthermore, the history of individual cars is not monitored. To compound these problems, an adequate statistical data base does not exist. Based on limited data in the literature (36), laboratory tests of thermal cycling to failure for Class B, C, and U wheels showed 750,000 cycles to failure at 200°C temperature change. This would correspond to an interval of 1000 miles for a 28" wheel. Although such a correlation must be treated with caution, it does provide a basis for preliminary assessment for field systems, pending availability of more data.

The problems of field quality hardware standards, operation and maintenance have been addressed in large measure by Southern Pacific and Florida East Coast Railways and provide a basis for further work. Cold weather limitations have been addressed at the hardware stage in part by CP Rail's 1976-1979 experience with an early Wheelfax system (see Section 4.1.4).

The performance of an eventual general-purpose device must address the question of defect characterization as well as identification (as is done at F.E.C.). Otherwise, the false-alarm rate will remain unacceptably high for most railroad operations.

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4.2 Summary of Initial Survey Findings

4.2.1 Incidence of Defects

The incidence of defects varies widely as a function of service. Detailed statistical data covering all factors involved is not available. However, certain generalizations can be made, though it is emphasized that the data given in this section is indicative only and taken from limited and widely different sources.

Condemnable shelling occurs in some 1% of all wheels in service per annum. Shelling and flats sufficient to cause rail damage can be detected by strain gauging of the rails.

Wear giving rise to condemnable conditions of "thin" flange and "high" flange can occur at one quarter the frequency of shelling in some services, e.g. coal trains.

Condemnable cracks have been identified at only 3% the frequency of shelling:

- . 40-60% of the cracks occur in the flange and rear flange face;
- . 5-30% of the cracks occur in the rim front face;
- . 10-40% of the cracks occur on the tread surface;
- . small percentage of cracks occur in the wheel plate or hub;
- . 4% of cracked wheels pass with cracks undetected and result in eventual failure and derailment.

Wide variation in distance travelled to failure coupled with widely varying rates of crack propagation makes scheduled removal of wheelsets from service in Canadian operation impractical.

Only one acoustic and two ultrasonic systems have been identified capable of detecting defects in wheels on moving trains.

The acoustic detection system developed by Dr. Finch at the University of Houston pioneered both hardware development and signal processing. However, the system was not fully developed and at the time that development was discontinued the false-alarm rate remained high. Factors considered in the present approach - controlled excitation, excitation at frequencies above 10 kHz, and intensimetry - were not tried.

4.2.2 Status of Wheel Crack Detection Technology

Ultrasonic systems are restricted to identification of tread defects.

The Wheelfax system has been developed to the level where a commercial service system is available. However, maintenance operations and the false-alarm rate are both areas requiring improvement.

The Deutsche Bundesbahn system developed by the Fraunhofer Institut and licensed to Krautkramer has addressed one of the major potential causes of false alarms inherent in the Wheelfax system by using EMATS transducers, though it is understood that the system still requires further development.

4.2.3 Defect Acceptance Criteria

The A.A.R. has a long history of developing standards and practices which have promoted uniform, safe and reliable railroad operations in North America. Wheel defects which could lead to failure have been identified and categorized, and criteria for their acceptance for continued operation or condemnation have been established.

These criteria are based on visual inspection and make no reference to such characteristics as depth of crack and sub-surface cracks and/or voids.

The potential advent of instrumentation which can characterize defects beyond the capability of the naked eye means that the question of accept/reject criteria will have to be addressed.

Automated inspection devices have the capability to provide significant data concerning a defect. To maintain railroad practice, the output of an automated system should be as simple as possible, preferably identifying a suspect wheel by A.A.R. "why-made" code, location, car number and yes/no accept/reject status.

The minimum crack size which must be detected has not been established. Cracks of less than 0.4" depth have not been associated with wheel failure leading to derailment. Conversely, the rate of crack propagation may vary widely. Subject to availability of more adequate data, a $\frac{1}{4}$ " (6 mm) deep crack should not pass undetected and an inspection frequency of every 1000 miles would appear reasonable.

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4.2.4 Cost-Benefit Considerations

Only one case of a cost/benefit analysis was identified. The theoretical conclusions differed from the apparent experience of Florida East Coast Railway that justified recent installation of a second Wheelfax system.

To be effective in the Canadian environment, there would have to be a network of inspection stations in the main yards of the railroads. The system would have to have a high reliability of defect identification. Payback would have to be over an appropriate period and would be based on the cost of system introduction offset, by elimination of costs of pertinent derailments plus applicable indirect costs of derailments, together with any other identifiable benefits.

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5.0

EXPERIMENTAL WORK

In order to evaluate the effects of wheel defects on the acoustical or vibration signature of a wheel, the following test program was established:

1. testing of the wheel behavior when submitted to a mechanical impact (i.e. resonant frequencies in the audible range);
2. testing of various configurations of mechanical impactors in order to determine suitable input transducer in relation to the defects being evaluated (frequency range, location of the impact on the wheel, etc.);
3. evaluation of the effects of faults on wheel signature (fixed and moving wheel) by comparing wheels on a same axle or by means of signal processing techniques;
4. testing of the wheel using ultrasonic techniques in order to find small tread cracks.

The idea behind the first three items was to review the work accomplished by the University of Houston in order to establish a level of reference for the acoustic technology. Following that, the intensimetry along with more advanced signal processing techniques had to be used in order to increase the sensitivity of the measuring probes and, thus, the discrimination level of the system.

In practice, we have found that the audible range of frequencies was suitable to identify:

- plate cracks;
- wheel wear (including high flange, thin tread, severely grooved wheels);
- tread defects.

However, although differences between the signature of a cracked (tread, flange, rim) wheel and a good wheel could be noticed, it was not possible to identify clearly the echo associated with cracks of less than 10 millimeters.

Most of these tests were made in parallel at Sherbrooke University and with the wheels available at CN's facility Pointe St-Charles, between January and April 1988.

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5.0 EXPERIMENTAL WORK (Cont'd)

Following that period, tests were performed with a piezoelectric transducer (ultrasonic technique) which showed that the higher the frequency at which the wheel was excited, the better the resolution of the system (i.e. identification of the echo associated with the crack on a time signal).

For this reason, various types of mechanical impactors were used in order to increase the excitation frequency from 10 kHz (typical impact-hammer) to 25 kHz. At this frequency, small cracks (= 10 mm) were still not easily detectable and tests were made with a large (50 mm) cracked wheel for which the echo was clearly detected. These tests were performed mainly between May and July 1988.

5.1 Test Program Methodology and Procedures

The initial survey of work on vibration analysis for detection of wheel defects has shown that to date a wide range of pertinent factors have not been adequately investigated.

A review was made of earlier work in acoustic defect detection to establish a program baseline, and a test program was therefore developed to address two fundamental areas:

- 1) characterization of the vibration signatures of different types of defects in wheels using acoustic frequencies;
- 2) development of an analytic approach to signal processing, as distinct from a comparative approach.

The objective of the preliminary defect characterization tests made at the CN Pointe St-Charles facility was to show that defects present in railroad wheels have an influence on their acoustic/vibration signature (AWS). Furthermore, through the analysis of the wheel signatures, it would be determined if it is possible to identify specific types of faults.

During the present phase, the faults tested were: cracks, tread defects (including shelling) and tread wear (high flange, thin tread).

The acoustical/vibration wheel signature was obtained by measuring the signal emitted (sound or vibration) by a wheel subjected to a mechanical impact which excited all the vibration modes.

5.1 Test Program Methodology and Procedures (cont'd)

Various configurations of impactors were used to evaluate their ability to excite the wheel. Finally, two types of impactor were used for the tests: an impact hammer and a steel pendulum.

The measuring probes were microphones, used alone or as a pair (intensimetry), and various types of accelerometers.

The signal processing techniques that were used varied, depending on the type of fault considered.

Most of tests performed at the CN Pointe St-Charles facility were based on the impact technique in order to find echoes related to cracks or investigate the wheel resonant frequencies that would give an indication of various parameters such as: diameter, wear, loading and presence of grease on the wheel. The procedure comprised:

- impacting the wheel and monitoring the input signal to determine its acceptability and characteristics (time duration, frequency range excited);
- measuring the acoustic/vibration signature (output signal);
- analysing the data (time and frequency signal, cepstrum technique, comparison of the two wheels on a same axle) in order to characterize the signature of a particular fault.

Other tests were made comprising rolling a wheelset along rails to monitor the vibration signal measured directly on the rail. These tests were conducted to demonstrate the fact that tread defects (build-up, shelling, flat spots) could be detected using microphones or accelerometers fixed on the rail.

5.1.1 Impactors

A mechanical impactor (ball-ended hammer) striking a wheel can be idealized as a sphere striking a plate. A key consideration is the duration of impact, since the shorter the duration, the higher the frequency excited.

The Hertz theory establishes the time duration of an impact between a sphere and a plate of given materials.

Simply stated, the duration of the impact (t) can be estimated with the following formulas:

5.1.1 Impactors (cont'd)

$$\text{Duration of impact} = t = \frac{2.94 \alpha}{V}$$

where: V = velocity of the sphere upon impact

$$\text{and : } \alpha = \frac{15}{16} \nu_1^2 \left[\frac{(1 - \nu_1^2)}{E_1} + \frac{(1 - \nu_2^2)}{E_2} \right] M^{2/5} R^{-1/5}$$

Where:

ν = poisson ratio

E = young modulus (lb/in²)

R = sphere radius (inch)

M = sphere weight (lb)

and subscripts 1 & 2 refer to the impactor and wheel respectively.

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From this theory, it can be shown that:

- a) The impact duration can be decreased by:
 - increasing the impact velocity;
 - increasing the radius of the sphere;
 - increasing the young modulus of the sphere.
- b) On the other hand the impact duration is increased by using a sphere with a higher density.

Tests:

Two approaches were used in the first phase of the preliminary study to excite the wheel mechanically in the acoustic range (20 to 20,000 Hertz) of frequencies. A mechanical hammer was used which had an integral force transducer to monitor the input signal given to the system, and a pendulum (mass with a hardened impact tip) which could be used with an accelerometer to monitor the impact.

5.1.1 Impactors (Cont'd)

The mechanical hammer has the advantage of being designed and tuned for this specific purpose and thus gives a precise reading of the input signal. However, the repeatability of this device is limited to the user's ability to reproduce the impact given to the wheel.

Moreover, the insertion of the force transducer with a given stiffness (typically 3×10^6 lb/in²) between the impacting mass and the wheel tends to limit the excitation frequency range by increasing the impact duration. Practically speaking, an impact hammer has a limiting impact duration of a minimum of the order of 0.1 millisecond (msec). Also, the removal of the force transducer increases the young's modulus of the impactor by a factor of 10 which results in an impact duration of 0.05 msec. By reducing by half the impact duration, the frequency range excited by the impact is doubled to about 20 to 25 kHz which is a limit from both the practical and the theoretical points of view. This limit has been reached in practice by means of the pendulum.

Experiments with these impactors have shown that tapping the wheel with a steel pendulum or a hammer excites a rich spectrum of wheel resonances. However, to obtain repeatability with this mode of mechanical excitation, it has been found that a good control of the impactor and the wheel (by means of guiding rails) will be essential.

Impact location on the wheel:

Various locations for impacting wheels were tested. In all cases (wherever the measuring probe or output signal is located), it was observed that impacting the back rim, near the flange, produces a signal with the best definition.

Preliminary tests observed showed that the measuring probe should ideally be placed at or close to the impact location, to prevent loss of definition of the signal. Another preferential location in the acoustic range of frequencies which is easier to implement in practice, is on the other side of the wheel at a location corresponding to the impact point.

5.1.2 Measurement Probes

Among the transducers available for noise and vibration analysis, the following were considered in the preliminary phase of the project:

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5.1.2 Measurement Probes (cont'd)

- microphones
- accelerometers
- magnetic and capacitive transducers
- acoustic emission transducer
- EMAT
- proximeter
- ultrasonic piezoelectric transducer

For the present phase, conventional microphones and traditional (contacting) accelerometers were used for preliminary analysis.

The other types of transducers are described in Appendix D.

Microphones:

Microphones convert a sound signal to an equivalent electrical signal, which is then amplified for analysis by electronic instruments. Microphones have numerous advantages:

- they are non-contacting, so the wheel does not need to be touched;
- sonometry or intensimetry (if used in pairs) can be measured;
- frequencies from 0.01 to 140,000 hertz can be detected;
- operating characteristics are well defined and stable.

Various types of microphones exist such as electric-condenser, ceramic, or condenser. Condenser microphones are the most used in practice.

Microphones used in humid and adverse atmospheres, or for underwater sound measurements, are called hydrophones. They generally use piezoelectric ceramics as the sensitive element (voltage-generating element which converts sound waves into electric signals).

Accelerometers:

An accelerometer is an inertia-operated piezoelectric device that generates a voltage proportional to the acceleration of the pickup. Voltages proportional to velocity and displacement of the vibrating body are also obtainable by the use of electronic integrating networks to convert the voltage generated by the pickup. This type of pickup has the advantage of small size, light weight, wide frequency range, and a low sensitivity to extraneous environmental influences including temperature fluctuations. Although, accelerometers eliminate the signature modification associated with the coupling between the air and the

5.1.2 Measurement Probes (Cont'd)

wheel surface, traditional accelerometers have the disadvantage of requiring physical contact with the wheel.

An accelerometer has very wide frequency sensitivity (fraction of a hertz to 60 kHz) and dynamic ranges with good linearity throughout the ranges. It is relatively robust and reliable so that its characteristics remain stable over a long period of time. Another important characteristic is that this transducer is reversible, i.e. the accelerometer can act as an exciter if a current is applied to it.

5.1.3 Instrumentation

The following instruments were used in the experiments:

Acoustics Measurements

- Intensimetry probe and accessories Brüel & Kjaer, type 3519.
- Microphones sets Brüel & Kjaer, type 4177 and 4178.
- Sound level calibrator Brüel & Kjaer, type 4230.

Vibration Measurements

- Accelerometers Brüel & Kjaer, type 4339 and 4393.
- Calibration exciter Brüel & Kjaer, type 4244.
- Accelerometers PCB model 302A06.
- Amplifier PCB model 480D09.
- Line drive amplifier Brüel & Kjaer, type 2644.
- Force transducer Brüel & Kjaer, type 8200.

Impactor

- Impact hammer PCB model 086B04.
- Pendulum.

Analyser

- Dual-channel digital analyser Brüel & Kjaer type 2032.

Computer

- Hewlett Packard 9000 series and accessories (disk drive, plotting table, printer, etc.).

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5.2 Studies by University of Sherbrooke

To establish a baseline, a subcontract was given to the University of Sherbrooke at the beginning of the project to:

- review the ultrasonic crack detection method;
- analyse the vibration behaviour of railroad wheels;
- analyse the acoustic crack detection technique based on the cepstrum analysis.

5.2.1 Ultrasonic Crack Detection Method

The first objective of the study was to review the technology and to develop an experiment to demonstrate the capability of this method of crack detection.

For the experiment, a wheelset was built at a scale of 1:3 and a crack (saw cut) of 1 mm deep was made across the tread of one wheel.

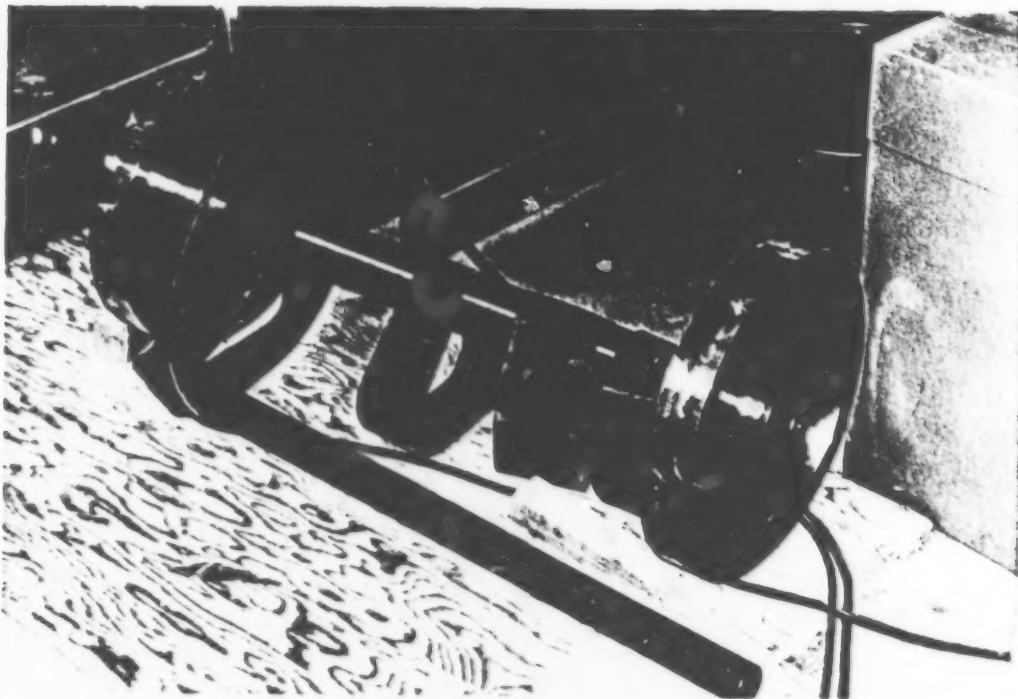


Fig. 5.1 Wheelset Tested for the Experiment (scale 1:3)

5.2.1 Ultrasonic Crack Detection Method (Cont'd)

To generate Rayleigh (surface) waves that propagate around circumference of the wheel, a very short impulse is required to excite the wheel. This was done by breaking a pencil lead on the surface of the wheel. The vibration signature was measured using an ultrasonic transducer (Brüel & Kjaer type 8312) with a frequency range of 200 to 800 kHz. The measured signal was amplified, filtered between 100 kHz and 2 MHz, and analysed numerically (DATA 6000 analyser) over a sampling period of 300 msec. This analyser can be used in a frequency range up to 1.6 MHz. The signal was analysed for a period of 0.6 msec.

A crack appears to the Rayleigh waves as a discontinuity in the material. Also when a crack is encountered, a percentage of the wave energy is reflected. The magnitude of the reflected wave (echo) depends on the size of the crack. The echos permit the detection of the crack.

These measurements were made successively on a sound wheel and one in which a saw cut was made to simulate a crack. Figure 5.2 schematically illustrates the impact location relative to the transducer.

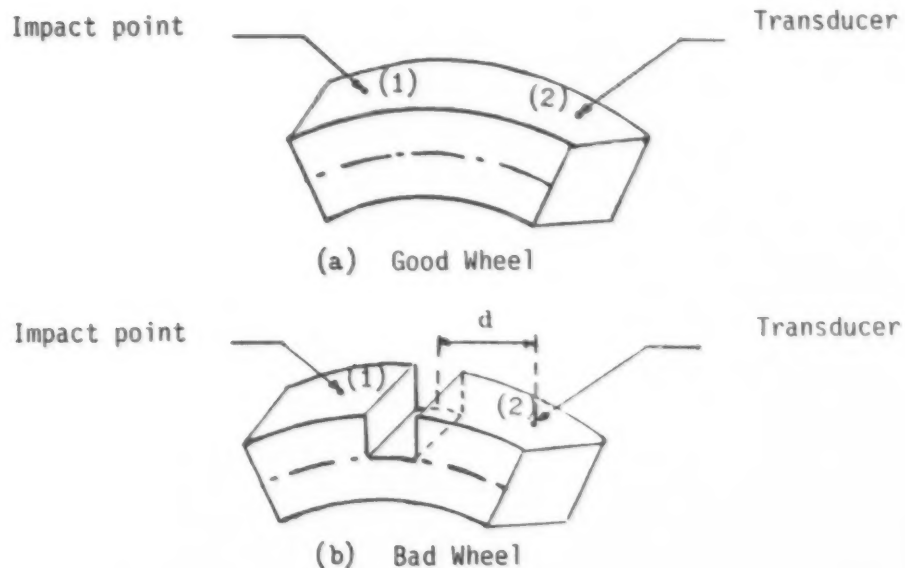


Figure 5.2: Location of Impact (1) Relative to the Transducer (2)

5.2.1 Ultrasonic Crack Detection Method (Cont'd)

The time signals amplified, filtered and sampled, are shown in Figure 5.3.

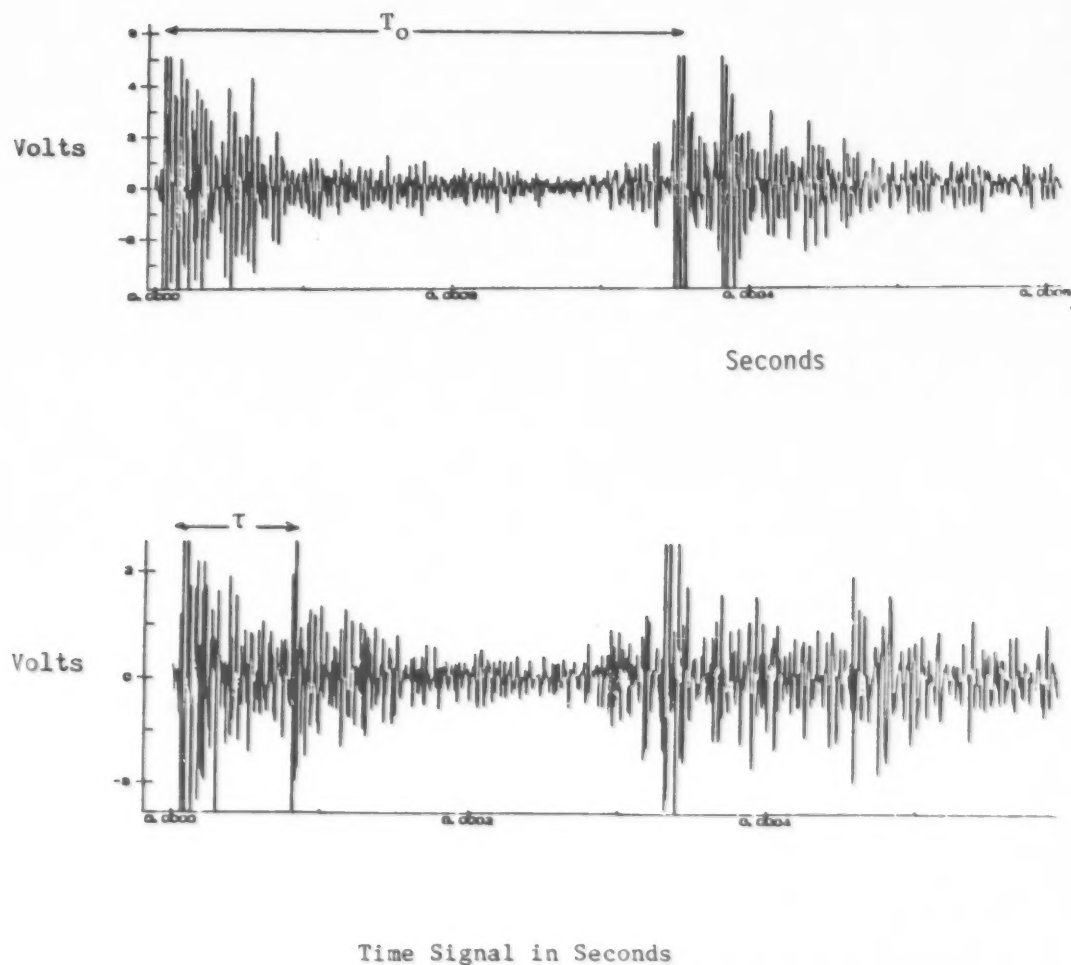


Figure 5.3: Time Signal
Upper Part: Good Wheel
Lower Part: Sawn Wheel (simulated crack)

5.2.1 Ultrasonic Crack Detection Method (Cont'd)

The important element to notice in the case of the good wheel is the time interval between the initial impulse (impact) and the following impulse, which corresponds to the time required for the wave to propagate around the circumference of the wheel ($T_0 = 2\pi R/C_R \approx 330$ usec. where R = wheel radius and C_R = velocity of propagation of a Rayleigh wave in steel = 2930 ms^{-1}).

For the cracked wheel, an additional peak appears at the time $T = 2d/C_R = 76$ usec. (d is defined in Figure 5.2). This peak corresponds to the echo associated with the crack. Also, the time signal for a cracked wheel shows the fact that the second impulse amplitude is reduced compared to a good wheel.

Figure (5.4) illustrates the power cepstrum of the preceding time signals:

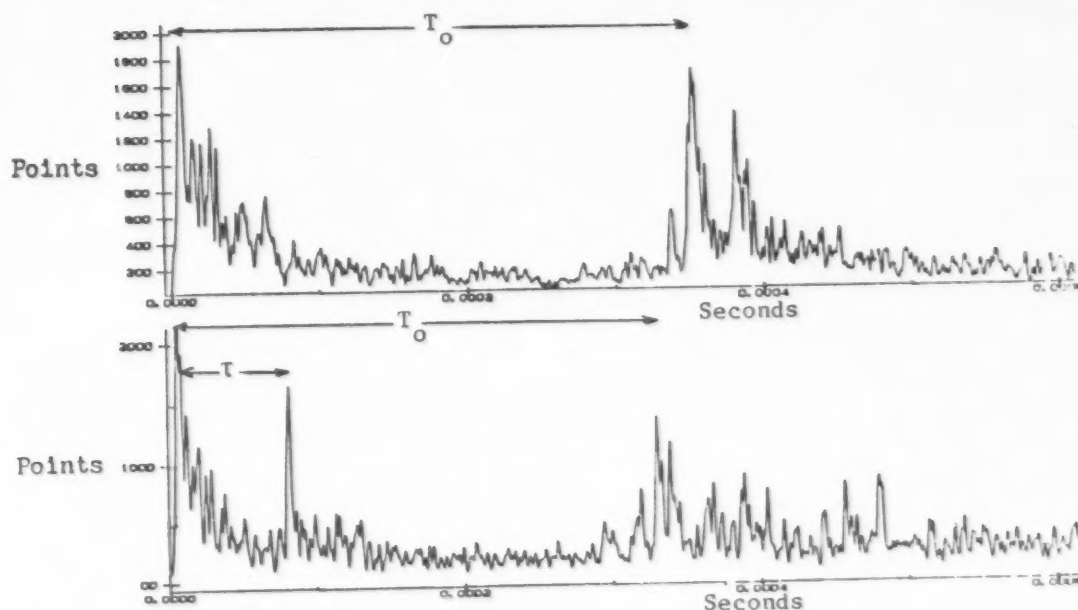


Figure 5.4 Power Cepstrum for the Time Signals of Figure 5.3.

This technique gives essentially the same information (T_0 , T); however, the echo is much clearer using this analysis technique.

5.2.1 Ultrasonic Crack Detection Method (Cont'd)

In conclusion, the ultrasonic technique using Rayleigh waves is able to identify the presence of cracks in the periphery (and close to the surface) of a wheel. The essential elements allowing the technique to be successful are:

- a very short impact is required in order to excite the wheel in the proper frequency range;
- the wavelength propagating in the material to be tested must be of the same order of magnitude as the crack depth to be detected.

5.2.2 Vibration Behaviour of Railroad Wheels

The theoretical analysis of a railroad wheel is very difficult due to the complexity of its structure. Stappenbeck describes an annular model which fits very well with what has been found in practice. He shows that in terms of energy content, the predominant vibrations are the flexion waves which are low frequency resonances.

Table 5.1 compares the resonant frequencies of a railroad wheel obtained on a theoretical basis and by measurements:

Table 5.1 Comparison of Measured and Predicted Resonant Frequencies (H_z)

Resonant Frequencies	MEASURED		PREDICTED			
	SNC (CN Wheelset)	Irretier	Dousis (Houston)	Stappenbeck	Irretier	Shivan Haran (Houston)
2nd	416	450	435	549	433	438
3rd	1056	1220	1147	1579	1201	1262
4th	1888	2160	2018	3049	2173	2363
5th	2816	3140	2990	4948	3268	3656
6th	3712	-	4012	7272	-	4991

5.2.2 Vibration Behaviour of Railroad Wheels

It can be seen that the resonant frequencies given by the Dousis, Shivan Haran and Irretier models are in close agreement with the measured values. The Stappenbeck model gives higher values.

SNC Comments:

Preliminary measurements at the Pointe St-Charles facility showed that, as would be expected, the various types of wheels found in the railroad industry each have their own resonant frequencies. It is difficult to compare wheel resonant frequencies without knowing the type of wheel, degree of wear, metallurgical composition, etc. The authors considered in this comparison do not fully describe the wheel characteristics and, for this reason, the variation in the results could easily be explained.

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique

Theoretical analysis and simulation were done first in order to verify the technique with simple, known signals. Thereafter, measurements were made on a wheelset with one good wheel and one wheel with a large crack (saw cut).

Theoretical Analysis

To verify that cracks can be identified in wheels using the cepstrum analysis, an analytical approach was first used. It was shown that by using a repetitive signal (equivalent to a series of pulses as seen from a transducer mounted on the wheel) which attenuates over time, and by applying successive signal processing techniques, cracks could be shown. The cepstrum and auto-correlation techniques were particularly interesting to emphasize the presence of a crack in the periphery of the wheel.

The simulation of these analyses is illustrated in Figures 5.5, 5.6 and 5.7, where T_0 represents the impulse measured by the transducer when a wave passes and T_1 represents the time at which the reflected wave appears at the transducer location.

In each of these series of figures, the upper part corresponds to a good wheel and the lower part to a cracked wheel.

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5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

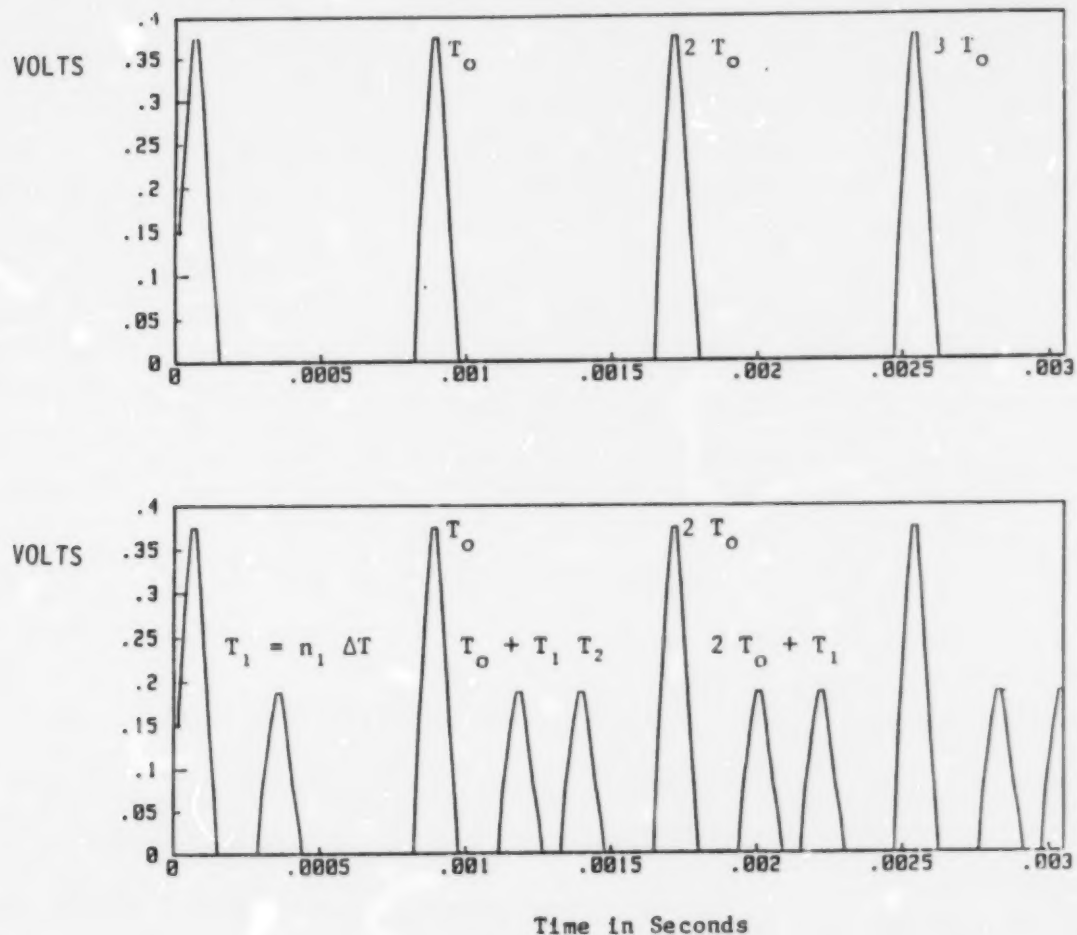


Figure 5.5: Upper Part: Time Signal, Good Wheel
 Lower Part: Time Signal, Cracked Wheel

The condition assumed to simulate the wave reflection caused by the crack is that its amplitude corresponds to 50% of the initial amplitude of the pulse.

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

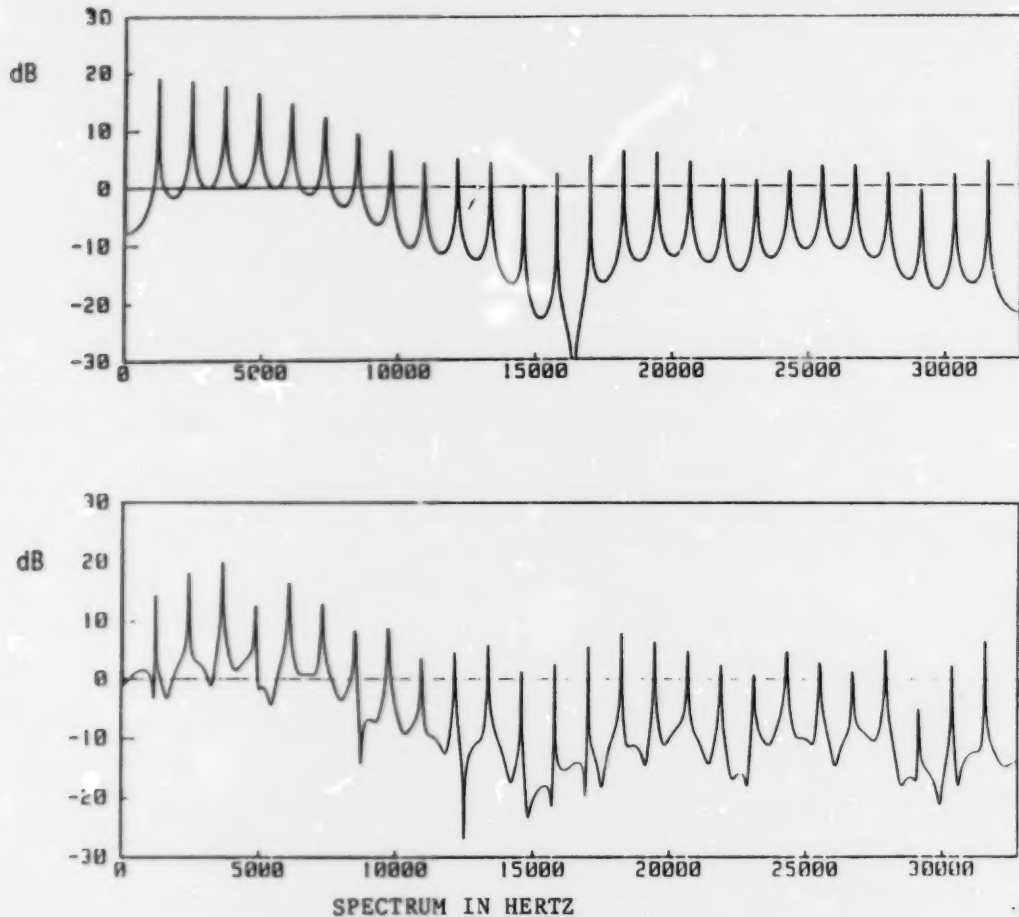


Figure 5.6: Power Spectrum of the Time Signal
Upper Part: Good wheel
Lower Part: Cracked wheel

The upper spectrum is typical for an impulsive time signal. The frequency at which the first lobe ends corresponds to the inverse of the impulse duration (frequency = $1/\text{time}$). Also, the time signal, which is a series of impulses, corresponds to a modulation in the frequency domain with a spacing of $1/t$.

The lower part of the figure has the same basic characteristics but in a more complex shape due to the interaction between the initial pulse and the reflections.

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

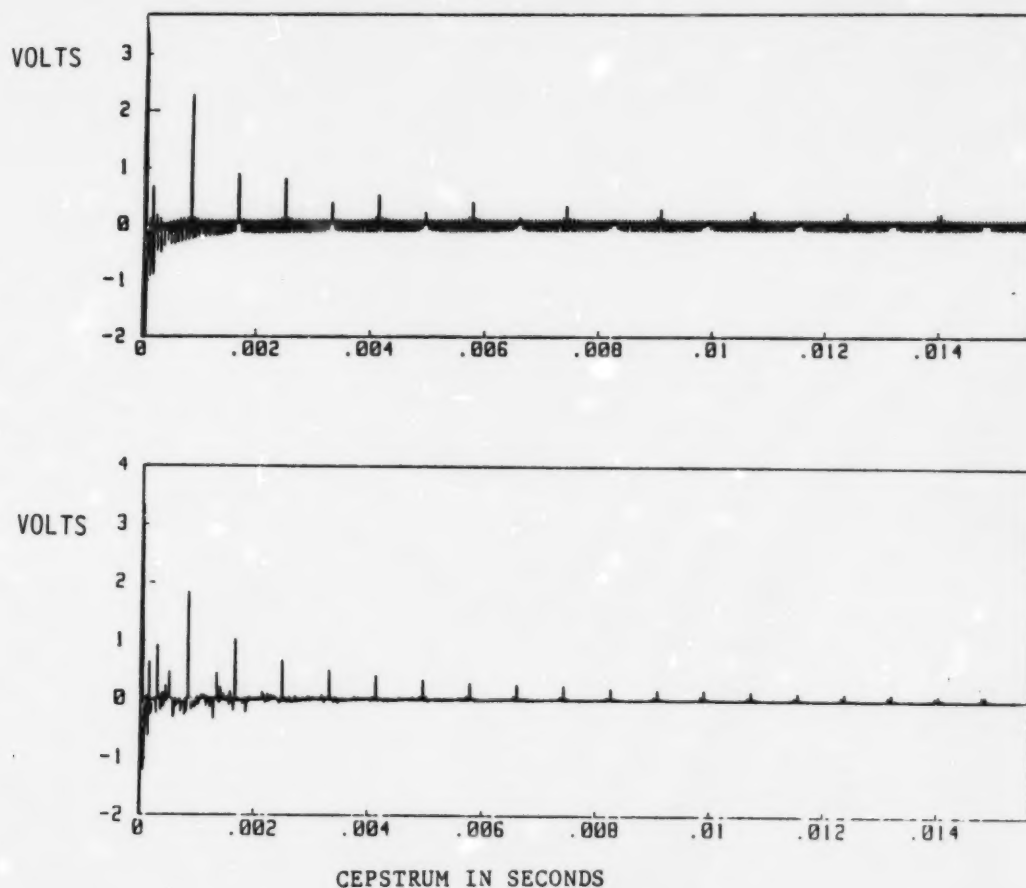


Figure 5.7: Power Cepstrum of the Time Signal
Upper Part: Good wheel
Lower Part: Cracked wheel

Both figures clearly show the peaks corresponding to the successive wave passage around the wheel. The lower part of the figure has additional peaks associated with the reflected waves evident during the first two periods.

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

For Figures 5.8 and 5.9, the time and frequency domain were respectively reduced to a period of 3 msec and a bandwidth of 3 kHz. The next signal processing made on the data (after cepstrum) is a lifting of the signal which consists in isolating a part of the cepstrum. This is done by a convolution of the cepstrum with a "hamming" window (a time-based filter used in digital analysis to avoid an artificial distortion of the frequency signal) for a period corresponding to T_0 .

The lifting is used to remove the characteristic duration of T_0 from the cepstrum. Following this, a Fourier transform of the modified cepstrum gives the lifted spectrum of the signal. This is illustrated in Figure 5.8. The auto-correlation function (which consists in returning to the time domain) is then calculated from the lifted spectrum.

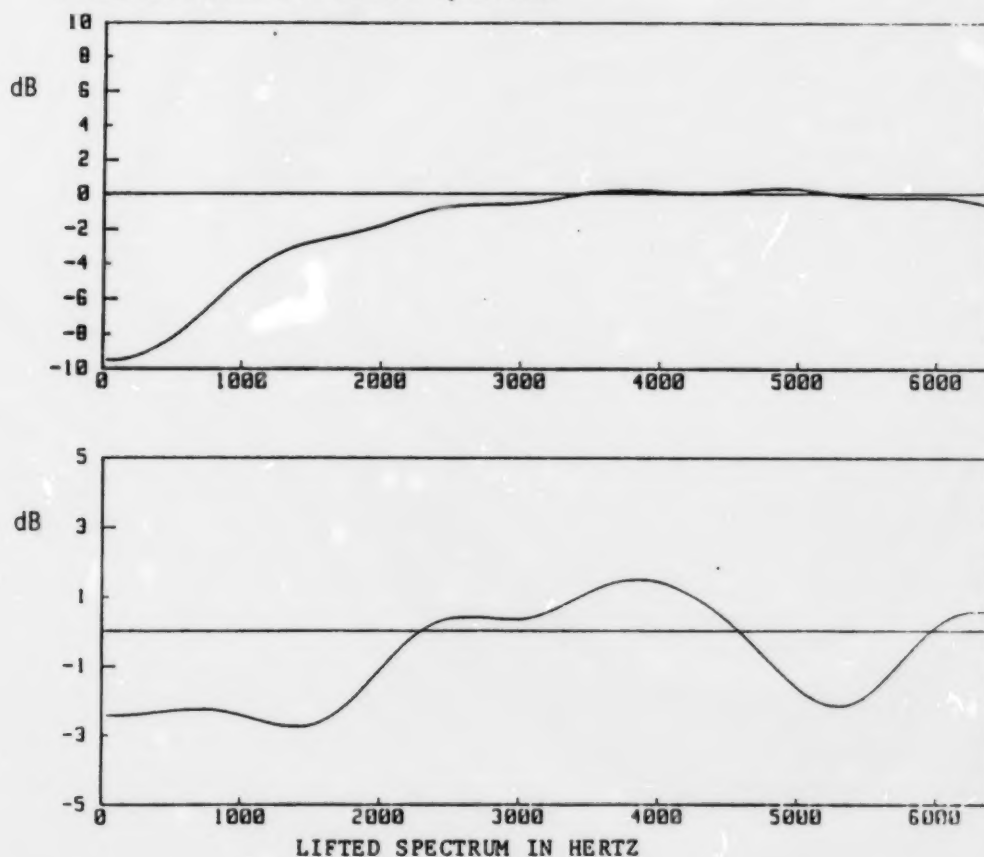


Figure 5.8: Lifted Spectrum of the Cepstrum
Upper Part: Good Wheel
Kower Part: Cracked Wheel

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

Figure 5.9 illustrates the auto-correlation function of the initial signal. We can clearly see the reflected wave on the lower part of the figure compared to a good wheel with no reflections.

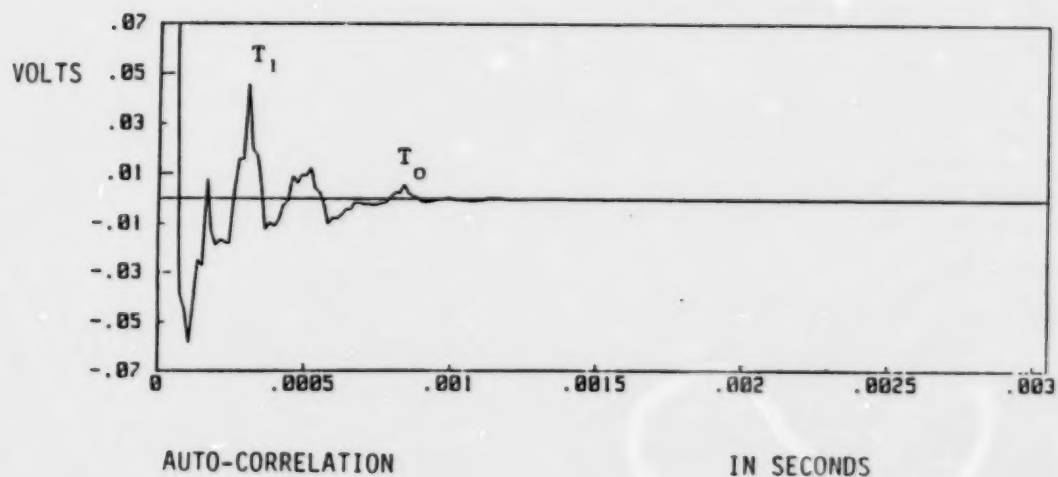
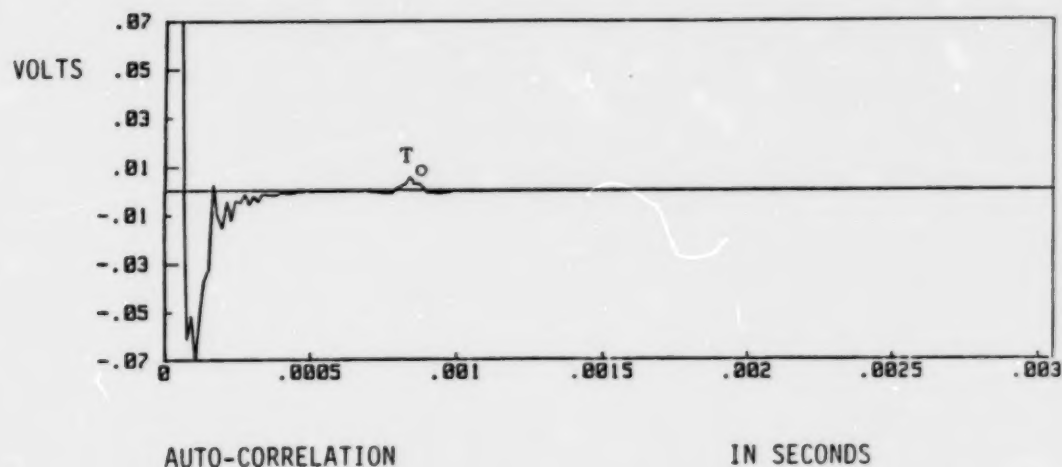


Figure 5.9: Auto-correlation Function of the Lifted Spectrum
Upper Part: Good Wheel
Lower Part: Cracked Wheel

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

Measurements on Railroad Wheels

The signature obtained from a railroad wheel excited with an instrumented mechanical hammer and processed in the manner described in the preceding section is now described.

Figure 5.10 schematically illustrates the instrumentation used for the tests. The impactor is a pendulum equipped with a hardened tip mounted on a force transducer. The measuring chain consists of vibration pick-up (accelerometers) or microphones connected to charge amplifiers and finally to a dual-channel digital signal analyser. A computer with its accessories is used to automatically control the analyser, perform additional calculations or signal processing, and/or to print results.

Figures 5.11 and 5.12 represent the time signal and the auto-spectrum of 5 typical impacts (i.e. the excitations given to the wheel). If we use as a reference that the energy at a given frequency is acceptable or significant if it possesses a quarter of the maximum energy given to a system, then it can be seen from Figure 5.12 that the bandwidth of the impactor is acceptable from 0 to 10 kHz. The tests performed on the wheels in this section are all based on similar excitation with a mechanical hammer.

The transducers used to measure the signature or the output of the wheel were:

- either
- accelerometers B & K type 4393 which have a weight of only 2.4 grams in order not to affect the wheel response, a sensitivity of $0.316 \text{ pc/msec}^{-2}$, permitting adequate measurements up to 16.3 kHz.
- or
- microphones B & K type 4135 with a flat response from 4 Hertz to 100 kHz and a sensitivity of 4 mV/Pa.

The time signal measured with accelerometers on a good and a cracked wheel are shown in Figure 5.13. The periodicity of the signature corresponds to the successive pulse passage at the probe location. It can easily be seen that in the case of a cracked wheel, the main peaks are attenuated and additional peaks appear between each period of T_0 .

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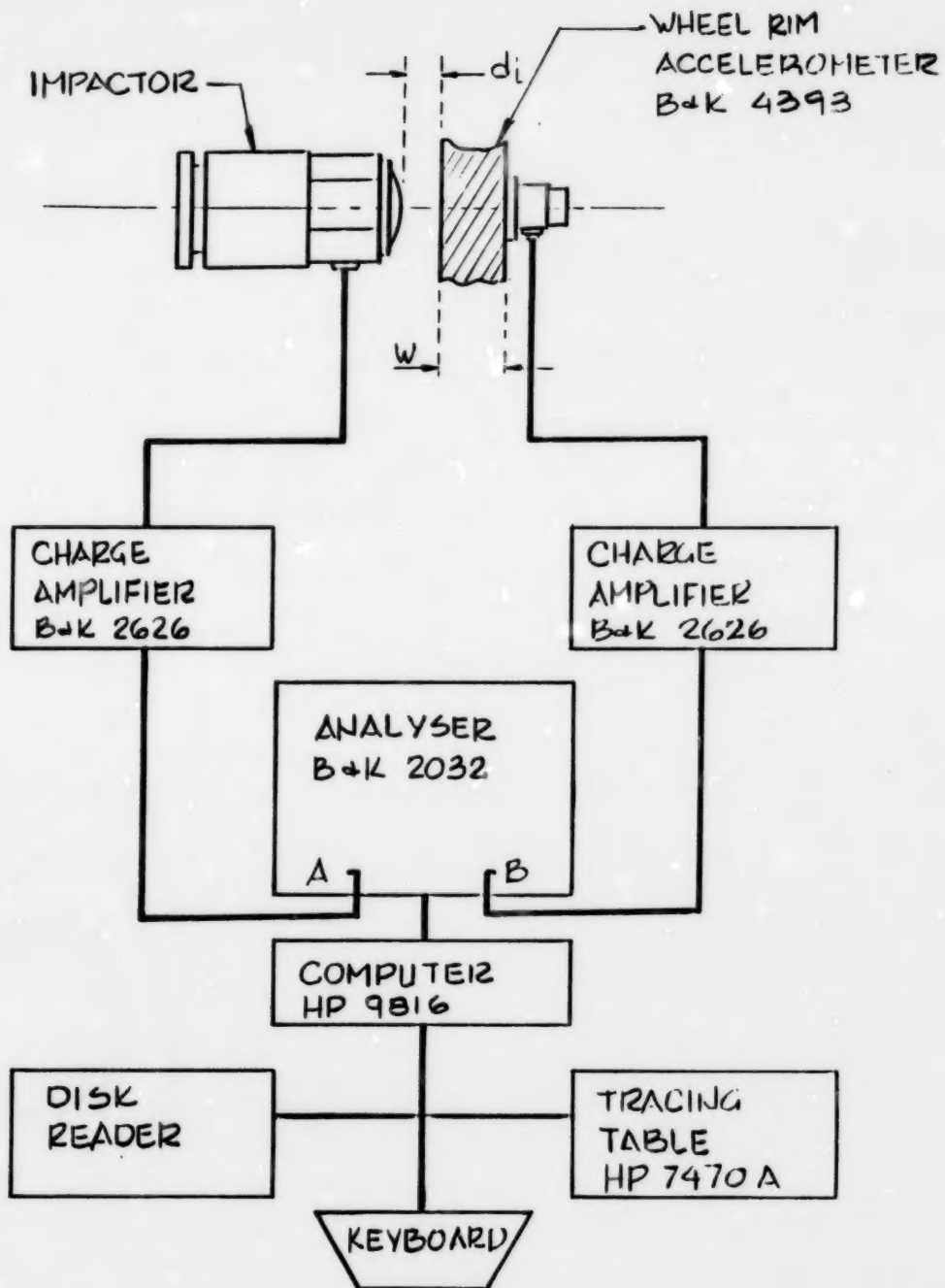


Figure 5.10: Measuring Instrumentation for Testing Wheels

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

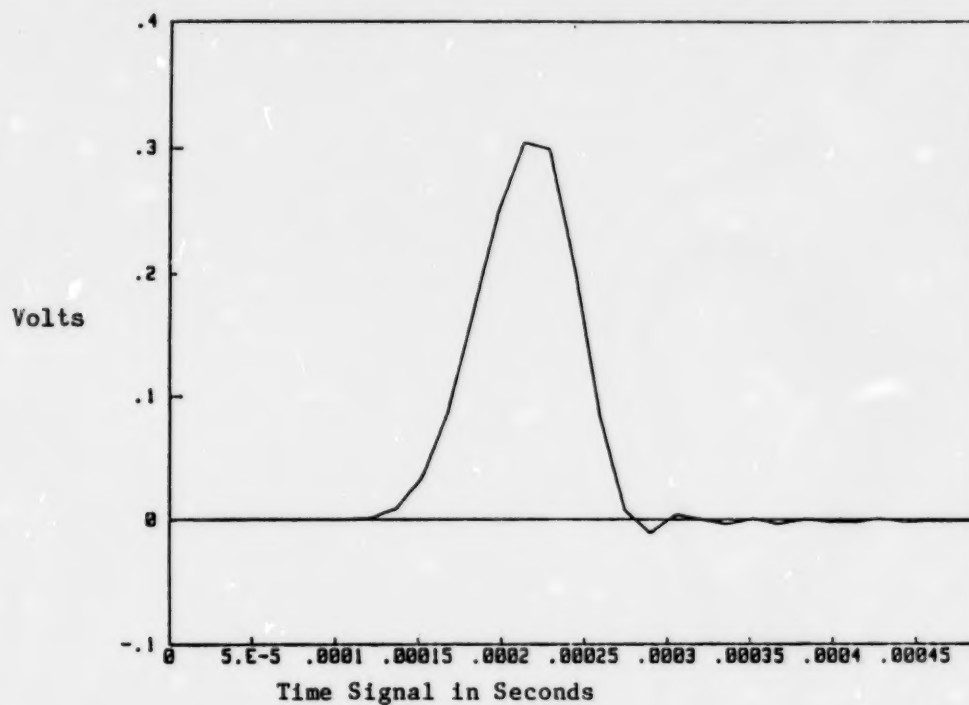


Figure 5.11: Impulse Shape Obtained with the Impactor on a Steel Wheel

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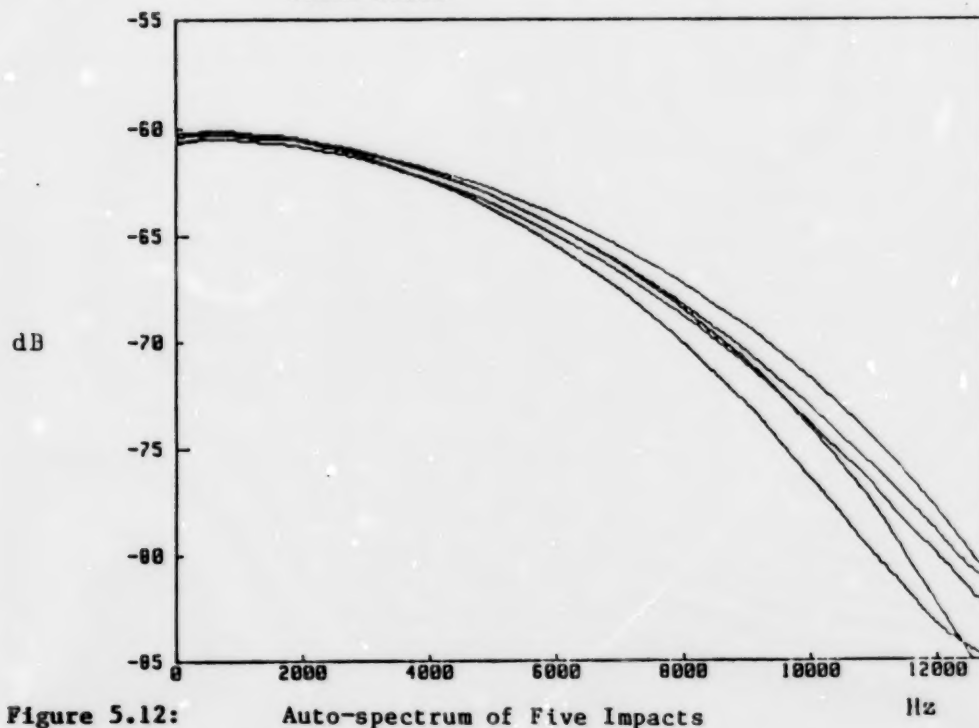


Figure 5.12: Auto-spectrum of Five Impacts

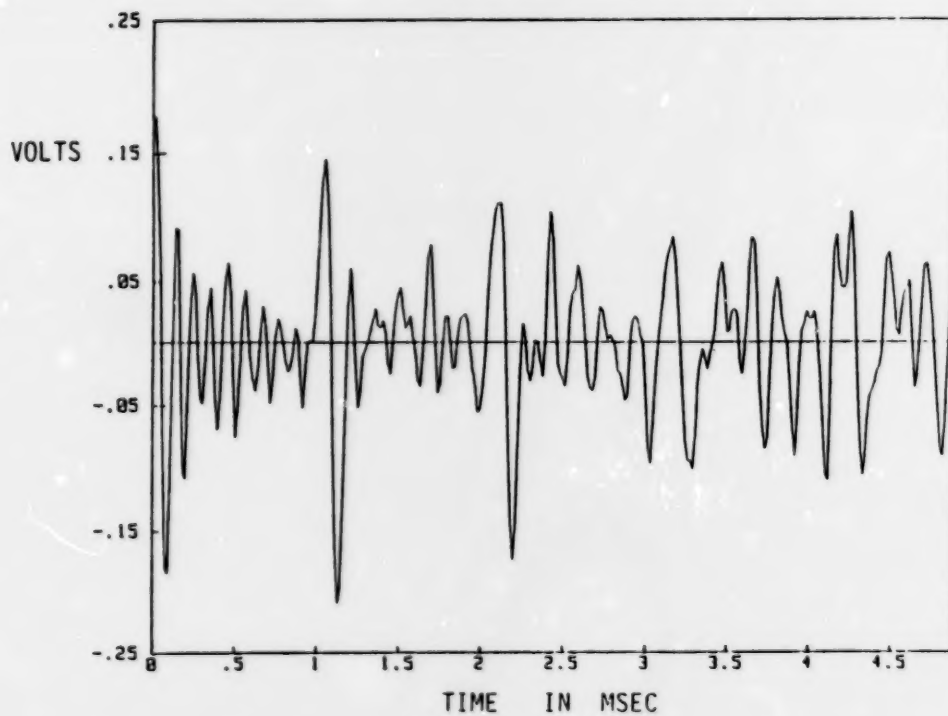
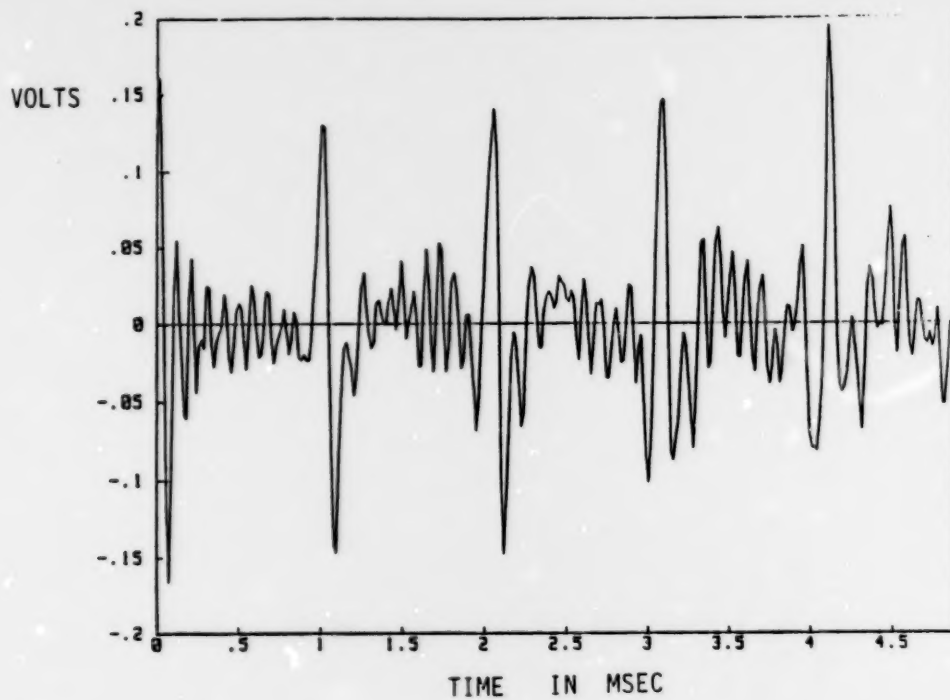


Figure 5.13: Time Signal Measured with an Accelerometer
Upper Part: Good Wheel
Lower Part: Cracked Wheel

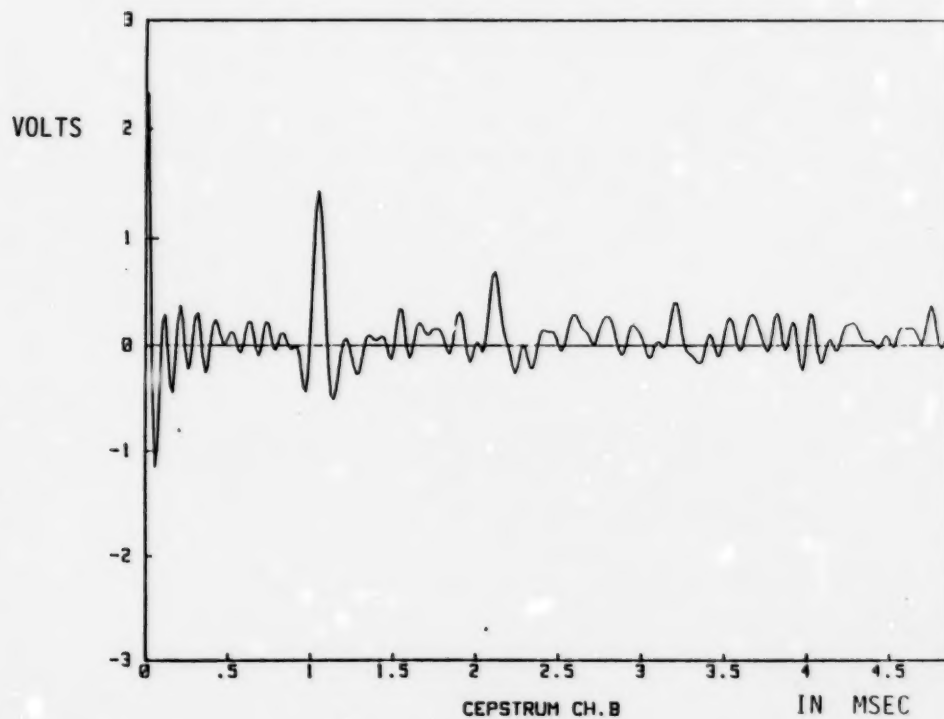
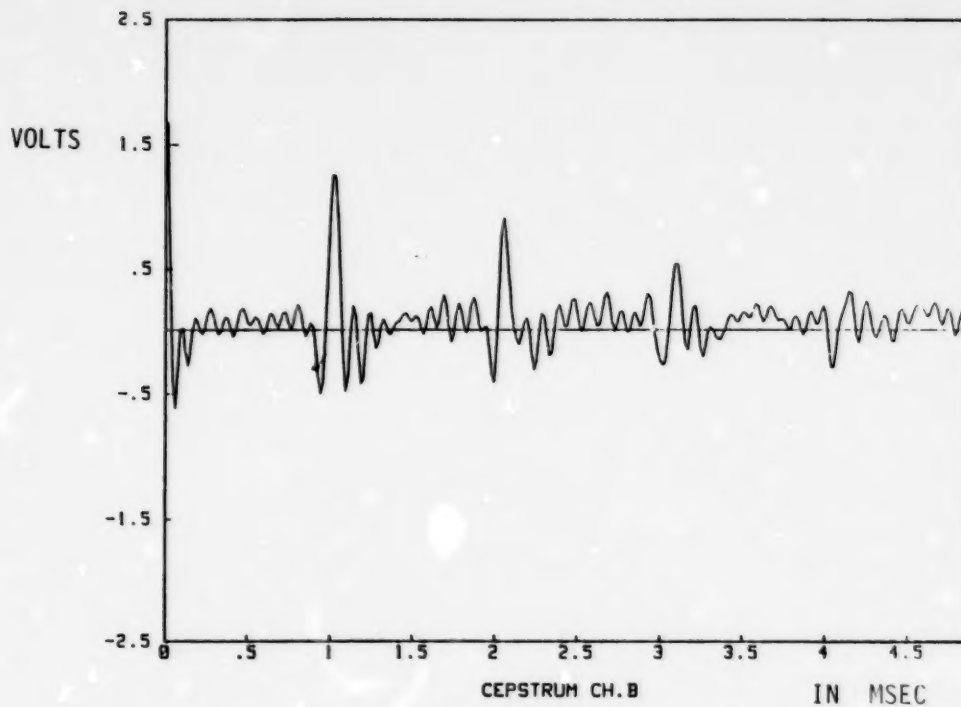


Figure 5.14: Power Cepstrum of the Time Signal
Upper Part: Good Wheel
Lower Part: Cracked Wheel

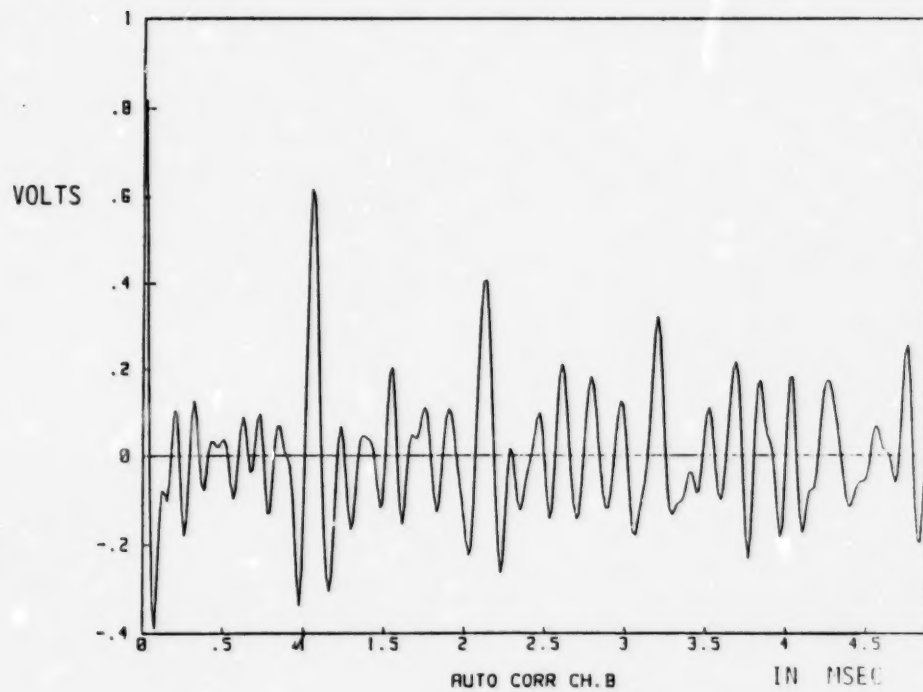
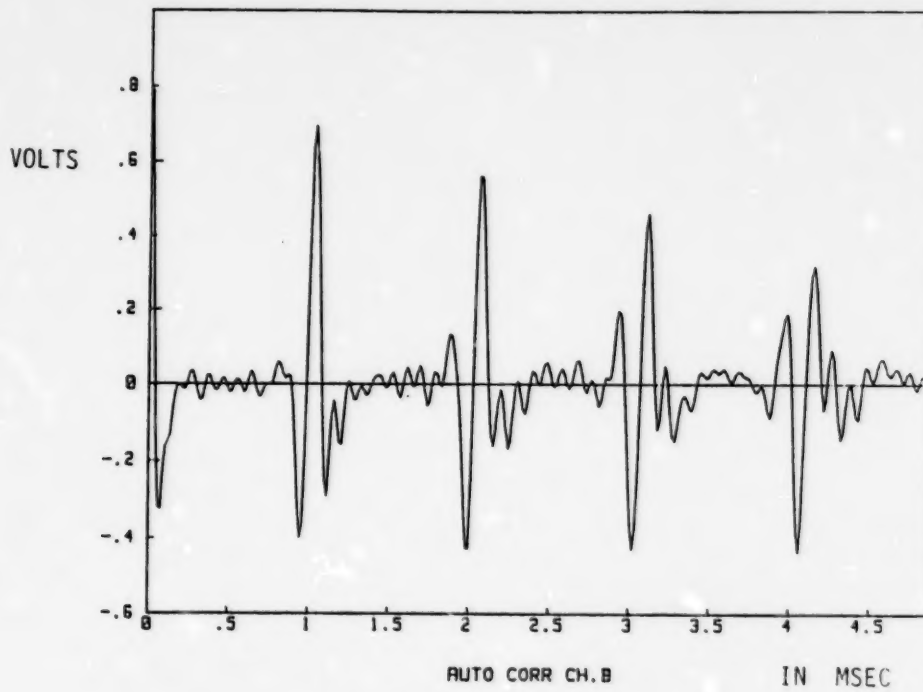


Figure 5.15: Auto-correlation Function
Upper Part: Good Wheel
Lower Part: Cracked Wheel

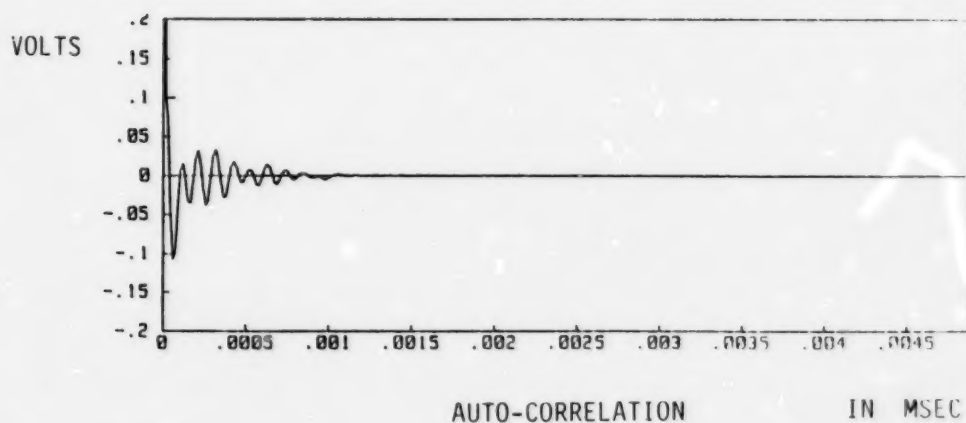
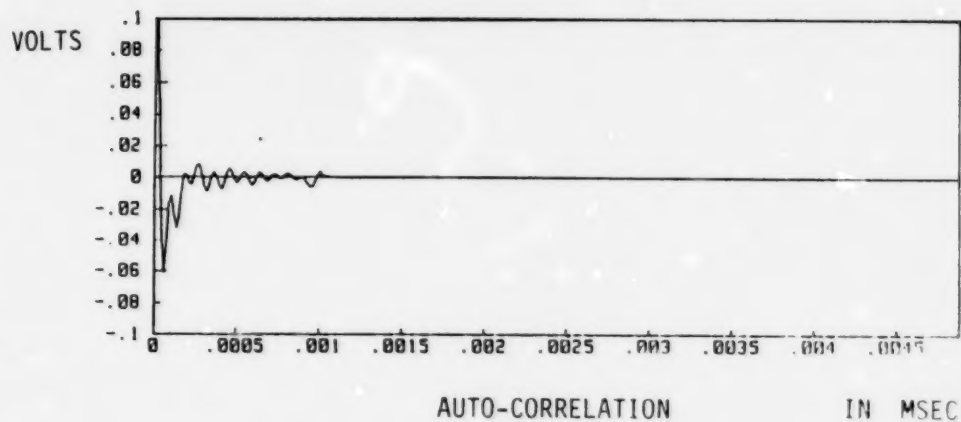


Figure 5.16: Auto-correlation of a Lifted Spectrum
Upper Part: Good Wheel
Lower Part: Cracked Wheel

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

The power cepstrum illustrated in Figure 5.14 also shows the periodicity of the peaks at an interval of T_0 . When a good wheel and a cracked wheel are compared, the peaks of the cracked wheel do not appear as clearly as those of the good wheel.

The auto-correlation signal illustrated in Figure 5.15 has the same differentiation as for the time signal except that the good wheel has a cleaner response between the successive peaks at T_0 periods.

The auto-correlation obtained from a lifted spectrum (Figure 5.16) also presents some differences in terms of the amplitude of the signal following the initial pulse between a good and a cracked wheel.

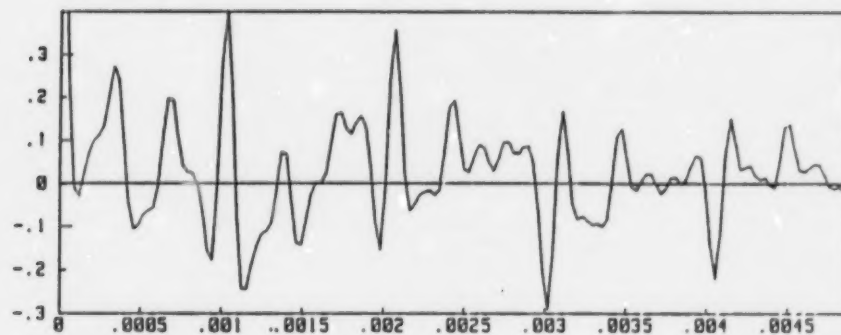
Figure 5.17 presents the intensimetry cepstrum obtained from a pair of microphones. Again, the periodicity of the pulse can be observed for the good wheel and for the first 2 or 3 msec for the cracked wheel. Although the two curves are different, the reflected wave is not identifiable due to the presence of additional peaks appearing between the main pulses.

These results require further investigation but probably can be associated with the coupling existing between the wheel surface and the surrounding air.

However, although all the signal processing techniques used show differences between a good wheel and a wheel with a single large crack, none of them clearly shows the reflected wave associated with the crack.

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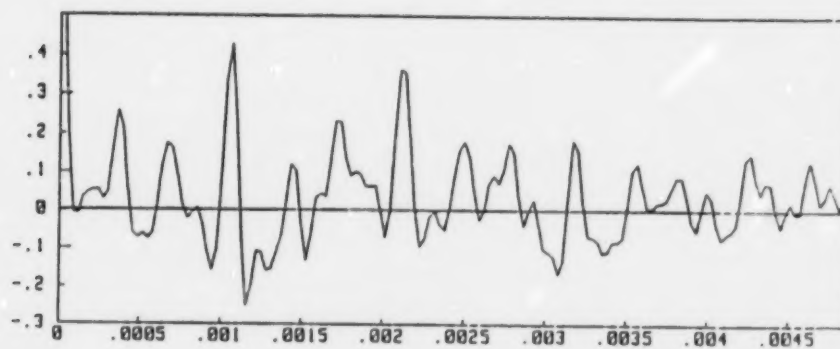
VOLTS



Cepstrum in Seconds

SNC

VOLTS



Cepstrum in Seconds

Figure 5.17 Intensity Cepstrum
Upper Part: Good Wheel
Lower Part: Cracked Wheel

5.2.3 Acoustic Crack Detection Using the Cepstrum Technique (Cont'd)

Discussion of Results

Many possible reasons can explain why differences between a good and a cracked wheel can be noticed, without giving enough information in the signal to clearly demonstrate the existence, location and size of the crack.

First, the frequency of excitation has been limited to 10 kHz which corresponds to a wavelength of 293 mm (approximately 1 foot). Considering the fact that we are seeking to identify a crack of about 50 mm, it can be intuitively deduced that the wavelength of the pulse is too large to be influenced by such a relatively small crack, despite indications in the literature that small crack identification would in any event be possible. Usually, the wavelength of the pulse should be of the same order of magnitude or smaller than the crack to be identified. In practice, the tests performed to date illustrate very well that a difference appears between a good and a cracked wheel. However, the frequency of the excitation mechanism must be increased in order to permit a precise evaluation of the defect and, following that of its size and location.

Another factor which reduces the efficiency of microphones and traditional accelerometers in detecting cracks in the signal is the influence of the lower modes of vibration of the wheel. When a wheel is mechanically impacted, all its modes (from zero to the highest excited frequency) are set into vibration. However, the lowest modes of vibration (flexion waves) are highly energetic and can mask the higher modes (Rayleigh or surface waves) which propagate over the wheel circumference and are used for crack detection. Also, the ideal transducer should be insensitive to the lower frequencies and be able to measure high frequencies (highly sensitive). Traditional microphones and accelerometers can measure high frequencies but cannot filter out low frequency noise. Thus, even if these transducers have a high dynamic range, the highest frequencies of interest can be masked by the lowest frequencies.

Moreover, in the case of microphones, the coupling between the wheel surface and the surrounding air is better at lower frequencies, reducing still further their ability to monitor higher frequencies.

5.3

Signal Processing Investigations

Virtually all significant work on acoustic signal processing prior to the present project, applicable to defect identification in railroad wheels, was that performed at the University of Houston. The approach taken at the University of Houston was oriented to a comparative evaluation of output signals from the two wheels on a common axle, on a time and frequency basis. Excitation was by nominally identical impacts on both wheels by each of two spring-loaded hammers. In principle, similar wheels were assumed to be similarly excited, and any difference in the output signal would be due to a defect in one of the wheels. Some thirty indicators (patterns for pattern recognition) were developed involving significant calculation. The researchers made recommendations, for more advanced signal analysis from the cepstra on the same basis, but when their work was discontinued, none of these had been introduced as an integral part of the fault diagnosis.

In the present study an alternative approach has been taken, in which the records of both the input signal and output signals from a single wheel are combined as the basic data acquired for subsequent signal processing. To determine the input signal, the hammer was fitted with a force transducer. Because of the elastic properties of the transducer, the excitation frequency was limited to 10-12 kHz (tests were also conducted with excitation frequencies of 20-25 kHz without this force transducer). The signal processing requirements to determine the presence of a defect are thus analytic rather than comparative and any errors which might arise from unknown inputs are eliminated.

The characteristics amenable to an analytic approach to signal processing, and therefore of interest, are:

- o Time-based analysis of the signal, i.e. direct evaluation of the principal output characteristics:
 - repetitive, presence of echoes, etc.;
 - evaluation of attenuation of amplitude of the principal waves on a "per millisecond basis", i.e. pulse decay;
 - attenuation of high-frequency vibrations due to the shock-absorbing characteristics of the wheels.
- o Detailed analysis in the time domain

Detailed analysis is based upon the correlation of successive (attenuated) signatures from the initial input, i.e. an

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5.3 Signal Processing Investigations (Cont'd)

assessment of the extent to which the signal is a similar displaced version of itself as a function of the time displacement between two nominally identical repetitive waveforms.

If a waveform is compared with itself by a correlation process, it is called "auto-correlation". If, however, the waveforms to be compared are distinct, the process is called cross-correlation.

The applications of the auto-correlation function are (Ref. 1.6):

a) Detection of echoes (reflections) in the signal

If an echo (reflection) with a time delay of T_0 exists in the signal, the auto-correlation function will peak at $T = T_0$ and the value of the auto-correlation coefficient function at T_0 will give a measure of the relative strength of the echo (reflection).

b) Detection of periodic signals buried in random noise

The auto-correlation function of a periodic signal is also periodic, since a periodic signal will correlate with itself at a delay of one period T , two periods $2T$, etc. The random background noise signal will have an auto-correlation function which diminishes to zero with increasing delay and the periodic signal can therefore be detected after a certain delay time in the auto-correlation function.

In the case of application of the cross-correlation function, it could be applied to compare two wheels on the same axle.

o Detailed analysis in the frequency domain

- Transfer, or frequency response, function

This commonly used approach measures the transfer function of a physical system, in this case the wheel. The transfer function represents the ratio of two quantities (such as the output signal/input signal) which describes the system in the frequency domain, assuming that the system is linear. A measure of the validity of the linear model is performed using a "coherence" function.

5.3

Signal Processing Investigations (Cont'd)

- Excitation techniques (Ref. 1.6)

In most applications of system analysis or testing, where input-output relationships have to be measured, it is necessary to excite the system with a well-controlled and measurable input.

A very popular and convenient excitation technique for mechanical structures is impact excitation using an impact hammer.

Figure 5.18 shows the Brüel & Kjaer Impact Hammer Type 8202, with a force transducer on which an impact tip is mounted. When the structure is excited by the hammer, energy is transferred to the structure in a very short period of time, giving a typical input force signal as shown in Figure 5.19. The shape of this force signal depends upon the type of the hammer tip, mass of the hammer and the dynamic characteristics of the structure under investigation. As the frequency bandwidth of the force spectrum is determined by the length of the signal, these characteristics will determine the cut-off frequency of the excitation signal. The stiffer the hammer tip and the structure, the shorter the signal and the wider the frequency span. Extra mass on the hammer, shown as dotted lines in Figure 5.19, will widen the force signal and therefore lower the cut-off frequency. This is also illustrated in Figure 5.19 where curves for steel, plastic and rubber tips are shown with and without the extra mass on the hammer. The structure used was a stiff plate.

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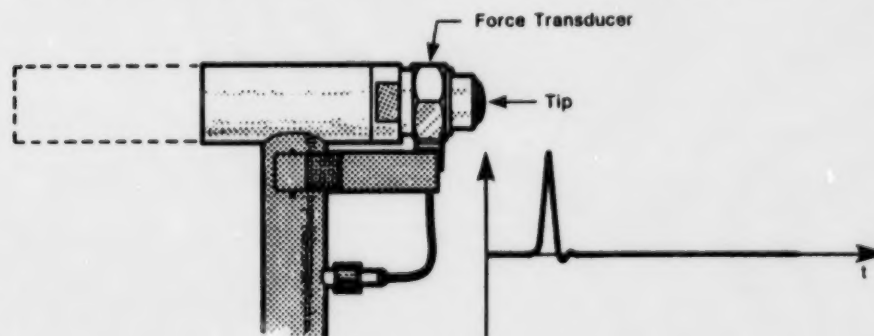


Figure. 5.18: Impact Hammer (Brüel & Kjaer Type 8202) and a Typical Input Force Pulse

5.3

Signal Processing Investigations (Cont'd)

It should be kept in mind that the force measured by the force transducer is not the true force which is input to the structure. Denoting the effective mass of the tip as m and the effective mass of the hammer (minus tip) as M , the true force F will be given by $F = \hat{F} \frac{M + m}{M}$ where $\hat{F}$ is the measured force.

The effective masses take into account the material characteristics of the tip and the hammer. Therefore, the impact hammer should always be calibrated using a proper calibration mass before the measurements are performed.

The advantages of using impact testing are that it is very fast, only a few averages are needed and it is easy to use in the field. However, the force signal has a high crest factor which can make this technique unsuitable for non-linear systems. The limited control of excitation bandwidth is also a disadvantage.

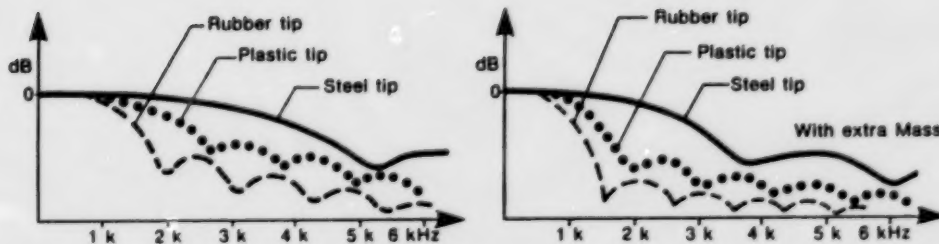


Figure 5.19: Typical Auto-spectra for Impact Hammer Force Pulses when Steel, Plastic, and Rubber Tips are Used, With and Without Extra Mass

5.3

Signal Processing Investigations (Cont'd)

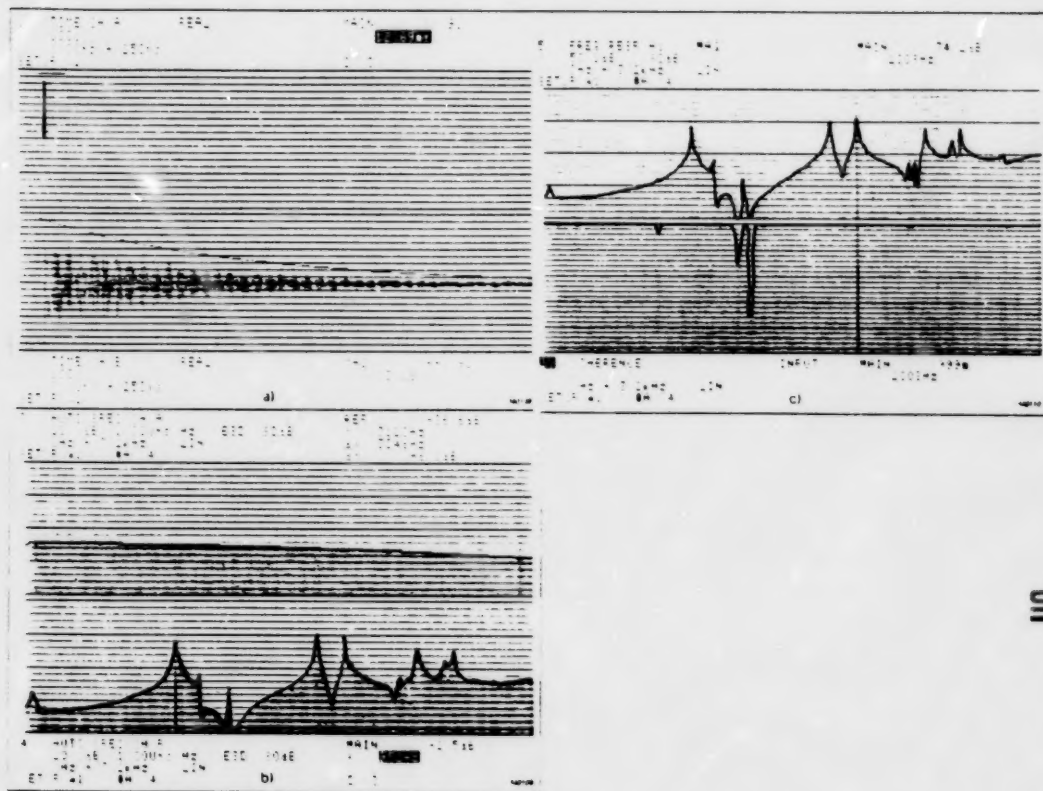


Figure 5.20: Analysis of a Mechanical Structure Using Impact Excitation

- a) Time ch.A and Time ch.B
- b) Auto-spectrum ch.A and Auto-spectrum ch.B
- c) Frequency Response Function $H_1(f)$ (magnitude) and Coherence Function

A practical application of the impact hammer technique on a mechanical structure is shown in Figure 5.20. A transient weighting function is applied to the force signal in ch.A, which will increase the signal to noise ratio and exclude other force signals which are not fed into the structure. Exponential weighting is applied to the response signal (acceleration) in channel B in order to avoid leakage effects due to truncation of the signal at the end of the record and in order to increase the signal to noise ratio in the analysis. This exponential weighting will introduce leakage, but as it will have the same effect as additional damping in the system, correction can be made subsequently.

5.3

Signal Processing Investigations (Cont'd)

In Figure 5.20 (b) the input force spectrum and the response spectrum are shown. A steel tip was used on the hammer and it can be seen that the force energy spectral density dropped only 8 dB at 3.1 kHz compared to the levels at low frequencies. The magnitude of the estimated frequency response function $[H_1(f)]$ and the coherence $^2(f)$ are shown in Figure 5.20 (c). Notice that the coherence is 1 at all the resonance frequencies. The exponential weighting function used on the response signal will introduce leakage in the analysis, but since the signals repeat themselves, the leakage will be the same for each analysis. The leakage is therefore not detected by the coherence function.

- Zoom technique:

In the case where a particular frequency band needs to be analysed in further detail, a function known as the zoom technique can be used to increase the resolution in the zone of interest. However, only a correspondingly smaller part within the original frequency range can be analysed at a time.

This technique will be used to set the frequency shift of wheel resonances or to further analyse the higher frequency content of the wheel signature.

- Cepstrum technique (Ref. 2.13):

The cepstrum exists in various forms but all can be considered as a spectrum of a logarithmic (amplitude) spectrum). This means that it can be used for detection of any periodic structure in the spectrum, e.g. from harmonics, sidebands, or the effects of echoes. It is also shown, however, that effects which are convolved in the time signal (multiplied in the spectrum) become additive in the cepstrum, and subtraction there results in a deconvolution.

The application of the cepstrum to echo detection and removal is based on the fact that echoes give a period structure to the spectrum which in turn becomes a series of delta functions in the cepstrum, which are easy to locate and remove. Even in the case of non-ideal reflections, instead of a delta function, the cepstrum contains the impulse response of the reflection, and can thus be used to measure the properties of a reflecting surface.

5.3

Signal Processing Investigations (Cont'd)

This periodicity in the (logarithmic) spectrum transforms by an inverse Fourier transform to a series of harmonics in the cepstrum (either power cepstrum or complex cepstrum) with a spacing equal to T . Thus, the existence and delay time of echoes is much easier to establish in the cepstrum than in the auto-correlation function, where even perfect reflection would give a scaled-down version of the auto-correlation of the original signal at the echo delay time. Only in the limiting case of white noise would this be a delta function. Thus, the cepstrum is much less sensitive to the shape of the power spectrum, and this can of course be considered a direct result of the logarithmic conversion.

The other advantage of the cepstrum over the autocorrelation function is that the effect of the echoes is additive, and thus subtracting the delta functions from the cepstrum removes the effect of the echoes completely.

5.4

Test Results

This section presents the principal results obtained during the test period:

- the influence of impact hammer characteristics on the excitation frequency bandwidth of the wheel;
- the effect of tread wear on the wheel vibration signature;
- the effect of a single large rim crack on the wheel signature;
- the effect of track and tread defects on the vibration signal measured on the rail.

All the experiments, unless mentioned otherwise, were made using different configurations of mechanical hammers (instrumented or not) which were used to excite the wheels at frequencies up to 25 kHz (i.e. near audio range limits).

5.4.1

Effects of Impact Hammer Characteristics

As can be seen on the following three figures (figures 5.21, 5.22 and 5.23), the influence of a mechanical hammer configuration influences the impact condition and thus its vibration signature.

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Auto Spec Ch.A RMS Lin Avg: 1
CN9G, ROUND HEAD STEEL HAMMER

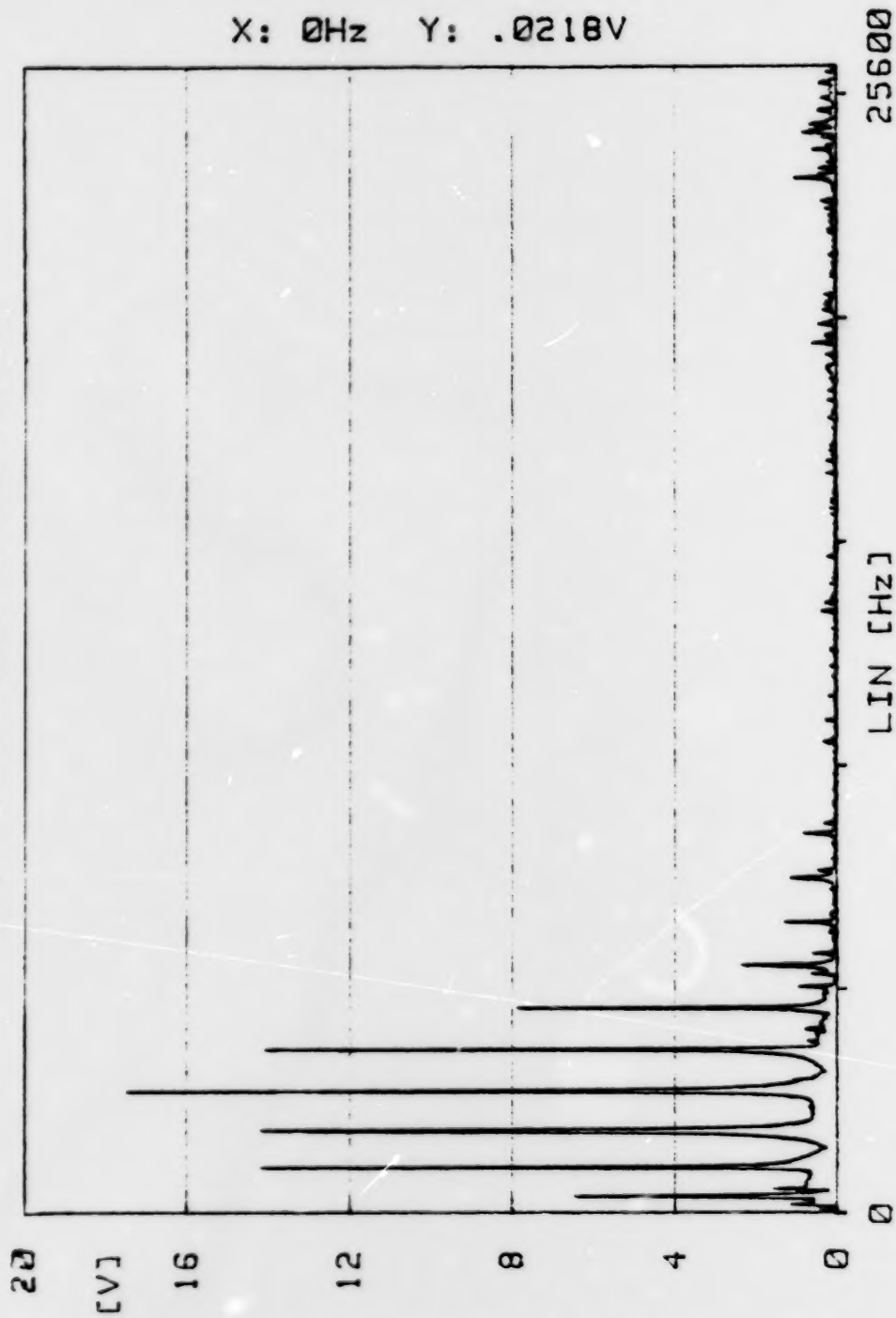


FIGURE 5.21

Auto Spec Ch.A RMS Lin Avg: 1
CN7D, PCB HAMMER, STEEL HEAD

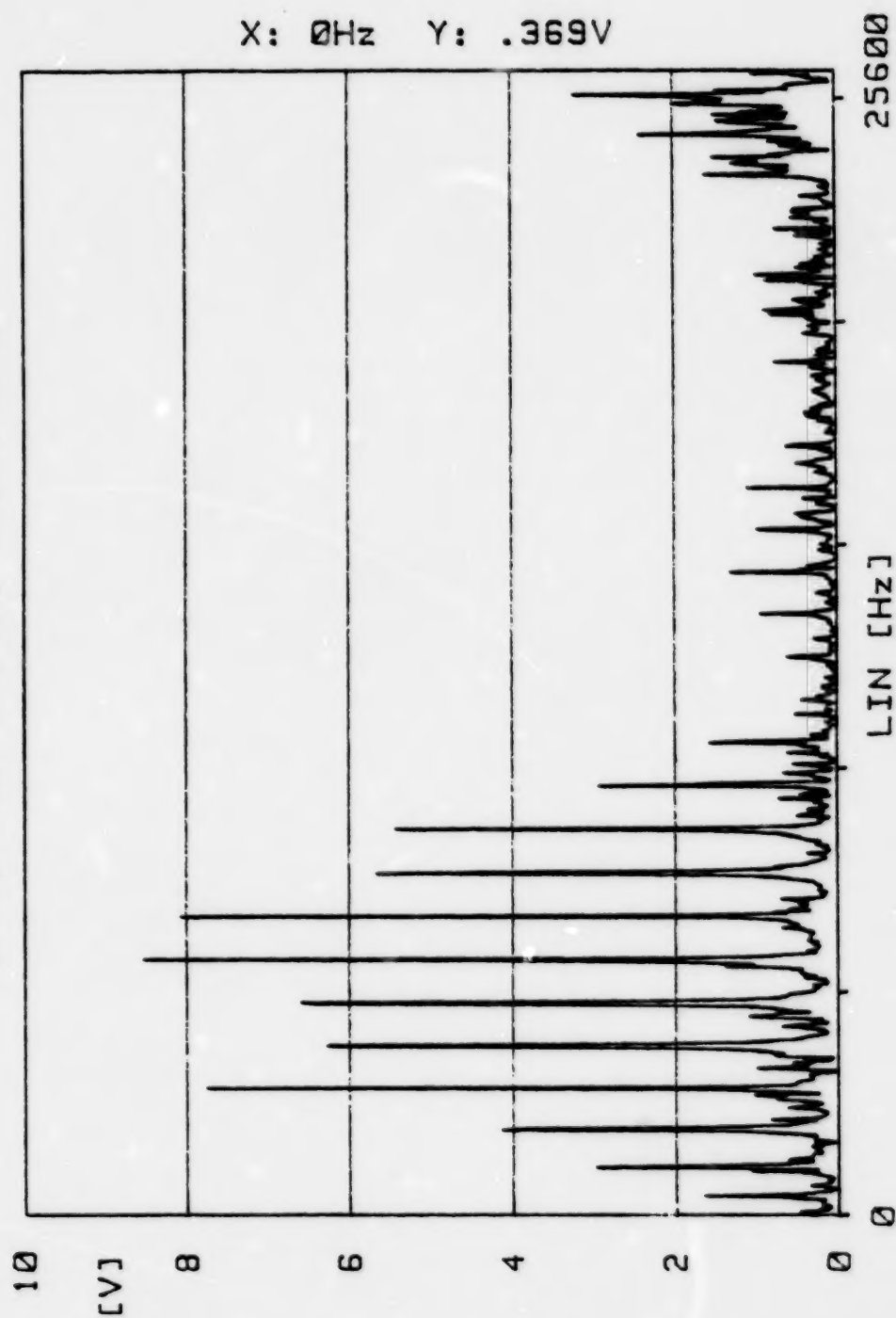


FIGURE 5.22

57C

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Auto Spec Ch.A RMS Lin Avg: 1
CN7D, PENDULUM, LARGE STEEL HEAD

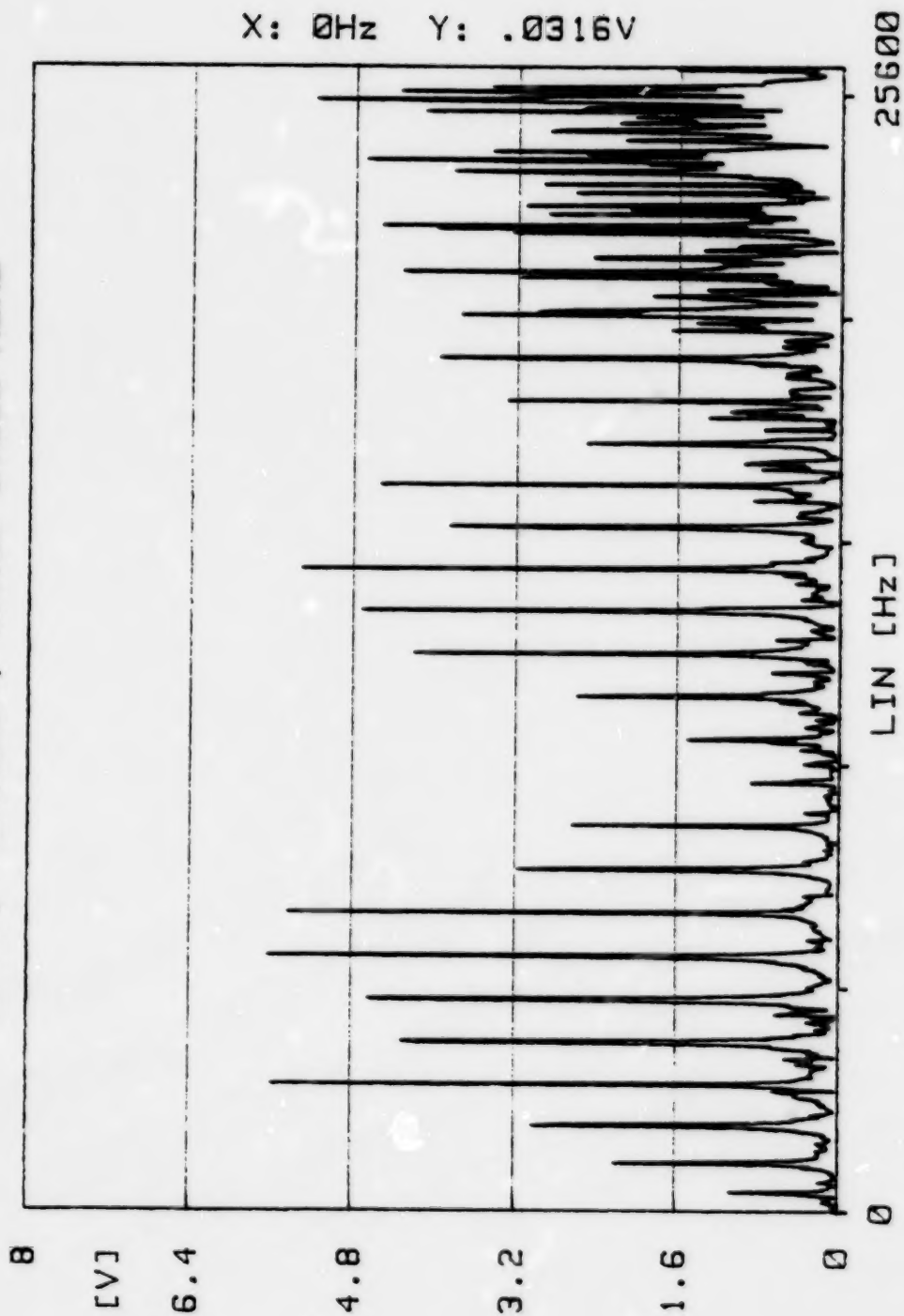


FIGURE 5.23

5.4.1 Effects of Impact Hammer Characteristics (Cont'd)

The input given to the wheel can be measured using an accelerometer mounted behind the hammer mass or by a force transducer mounted between the hammer tip and the impacting mass. By using an accelerometer, the rigidity of the transducer does not impose any limitation (except for its additional mass) in terms of the impact duration.

Figure 5.21 shows the vibration (acceleration) signature of a wheel impacted with a round-head steel hammer. This hammer (without transducer or accelerometer) is heavy and as such transfers much energy within the wheel. On the other hand the impact duration is long and, as shown, the wheel resonances are excited only up to around 5 kHz. This impactor configuration is similar to the tests made at Houston University and gives a good indication of the excited frequency range (0-5 kHz).

The following figure (5.22) illustrates the vibration (acceleration) signature excited with a PCB instrumented mechanical hammer (with force transducer behind the tip). Using this instrument with a steel tip excites the wheel resonances up to around 10 kHz. The energy level radiated by the wheel is also considerably diminished due to the fact that the hammer mass is lower than in the preceding case. These results correspond to the frequency range excited during the tests made at Sherbrooke University (see section 5.2.3).

The peaks at frequencies around 25 kHz are due to the accelerometer mounting resonances. As previously discussed, the force transducer mounted on the mechanical hammer was the limiting factor in terms of high-frequency wheel excitation.

Finally, Figure 5.23 illustrates the vibration (acceleration) signature of a wheel impacted with a pendulum having a large (tip radius) steel head.

The wheel resonances are excited up to around 25 kHz with such a hammer.

These tests have been made at the CN Pointe-St-Charles Wheel Shop.

5.4.2 Effects of Tread Wear on Wheel Vibration Signature

The following two figures (5.24 and 5.25) illustrate the influence of tread wear on the wheel vibration signature. In practice, as the wheel tread wears out, its resonant frequencies

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Auto Spec Ch.A RMS Lin Avg: 1
CN2D, HIGH FLANGE

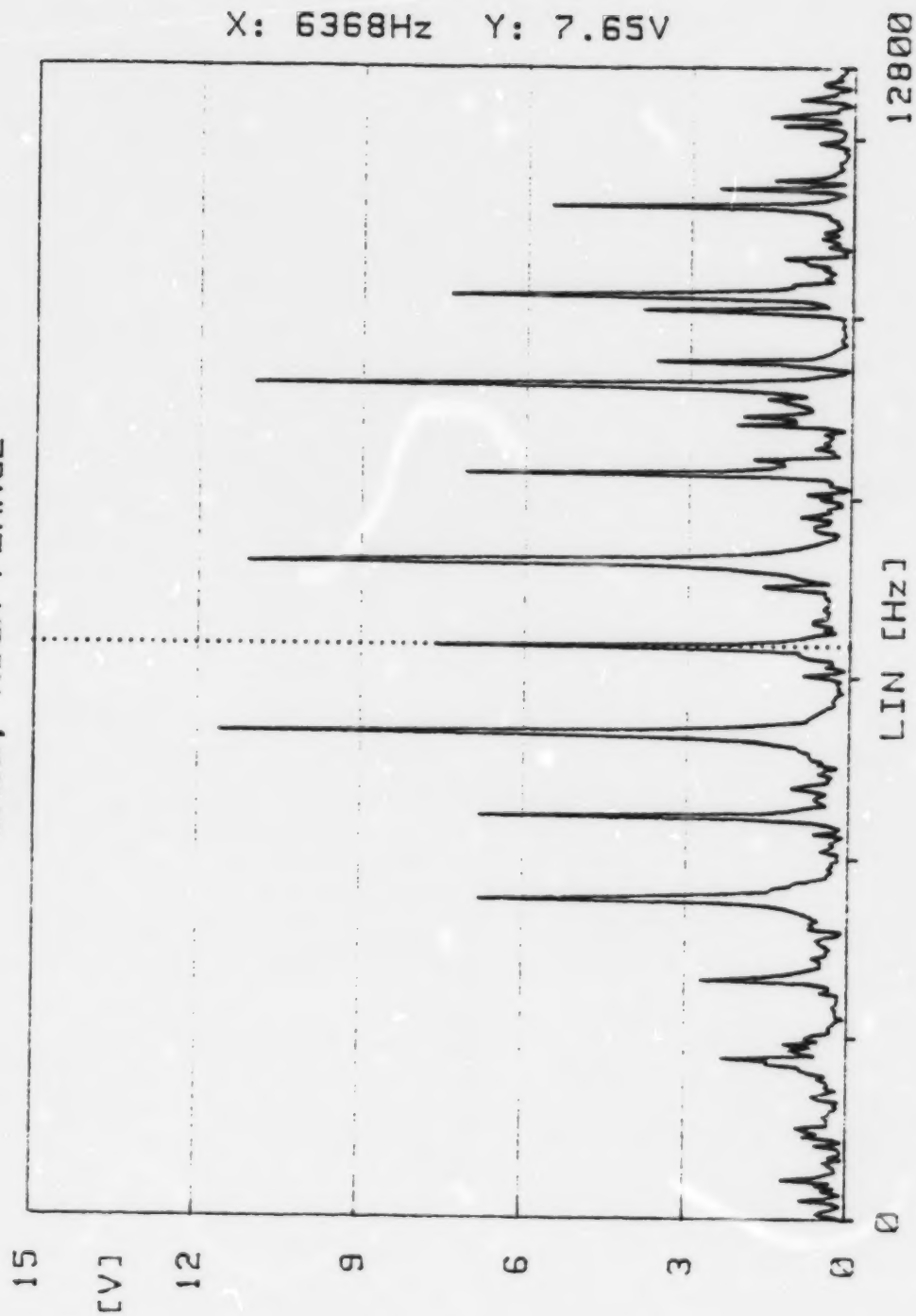


FIGURE 5.24

Auto Spec Ch.A RMS Lin Avg: 1
CN2G, HIGH FLANGE & THIN TREAD

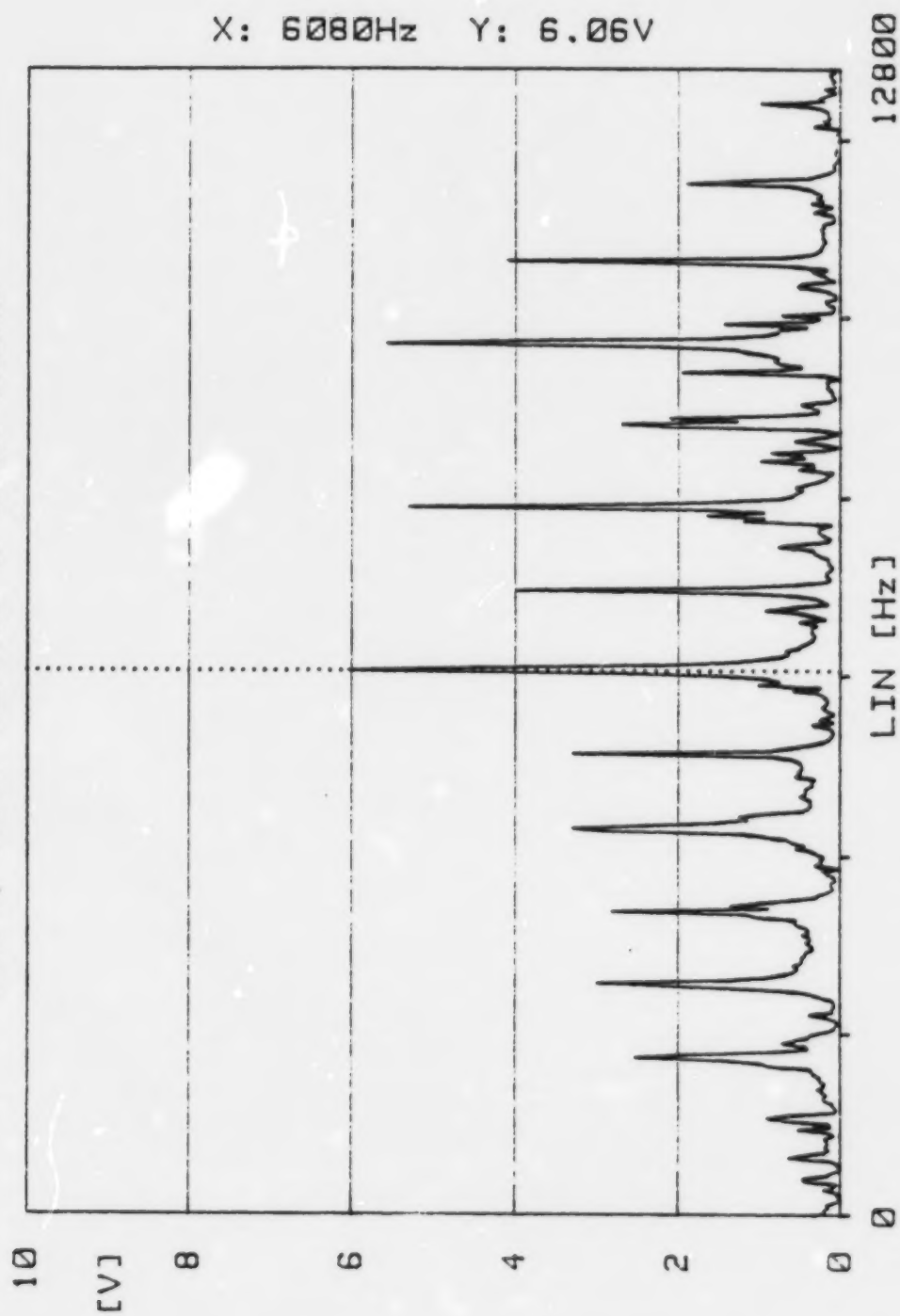


FIGURE 5.25

50C

5.4.2 Effects of Tread Wear on Wheel Vibration Signature (Cont'd)

diminish. In our case, two wheels on the same axle were compared, showing for example that the sixth resonance of the most worn wheel has decreased in frequency (relatively) from 6.368 to 6.080 kHz. Each of the wheel resonances shows the same pattern.

Although frequency variations of wheel resonances could be easily analysed by means of dedicated software, the practical approach is more complex due to the various types of wheels in use by the railroad companies.

It must be pointed out that the relative amplitude of the vibration signature measured on both wheels does not influence their resonant frequencies. These differences are due to the fact that the wheels were impacted by hand.

5.4.3 Effects of a Single Large Rim Crack on Wheel Signature

The following figures are an illustration of some of the techniques (see Section 5.3) which can be used to detect a wheel crack, i.e. time signal, auto-spectrum and cepstrum.

Figures 5.26 and 5.27 show the effect of a crack on the time signal of the wheel vibration signature.

In the case of a good wheel, the initial (impact) and successive (at 1 msec. intervals) pulses appear clearly for a time period in excess of 15 msec.

Comparatively, for the same wheel with a simulated (saw cut) large tread crack (2 inches long), the pulses can be identified for only 4 msec.

The reflections generated by successive pulses interacting with the crack drastically increase the complexity of the time signal and the energy content between the pulses.

Using digital signal processing techniques, the information contained in the initial time signal can be processed and expressed in terms of the frequency domain. Figures 5.28 and 5.29 show the auto-spectra of a good wheel and for a wheel with a simulated rim crack. The major difference between these two auto-spectra is the presence of additional peaks between wheel resonance frequencies.

Finally, on the same wheels used for the auto-spectrum (wheels used by University of Sherbrooke in their analysis), Figures 5.30

Time Ch.B Real
CN7G GOOD WHEEL

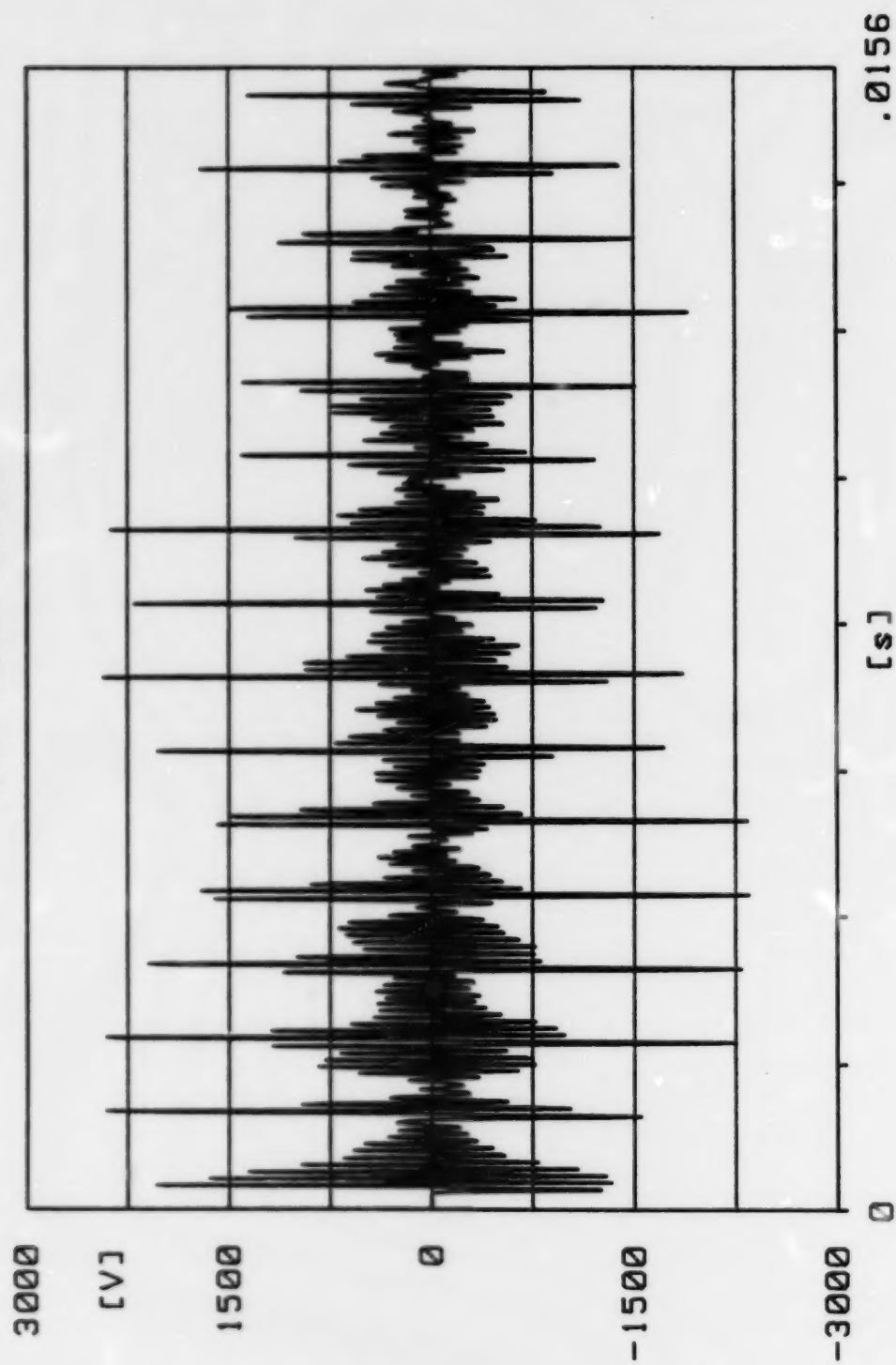


FIGURE 5.26

500

ENC

Time Ch.B Real
CN7G SIMULATED BIG FLANGE CRACK

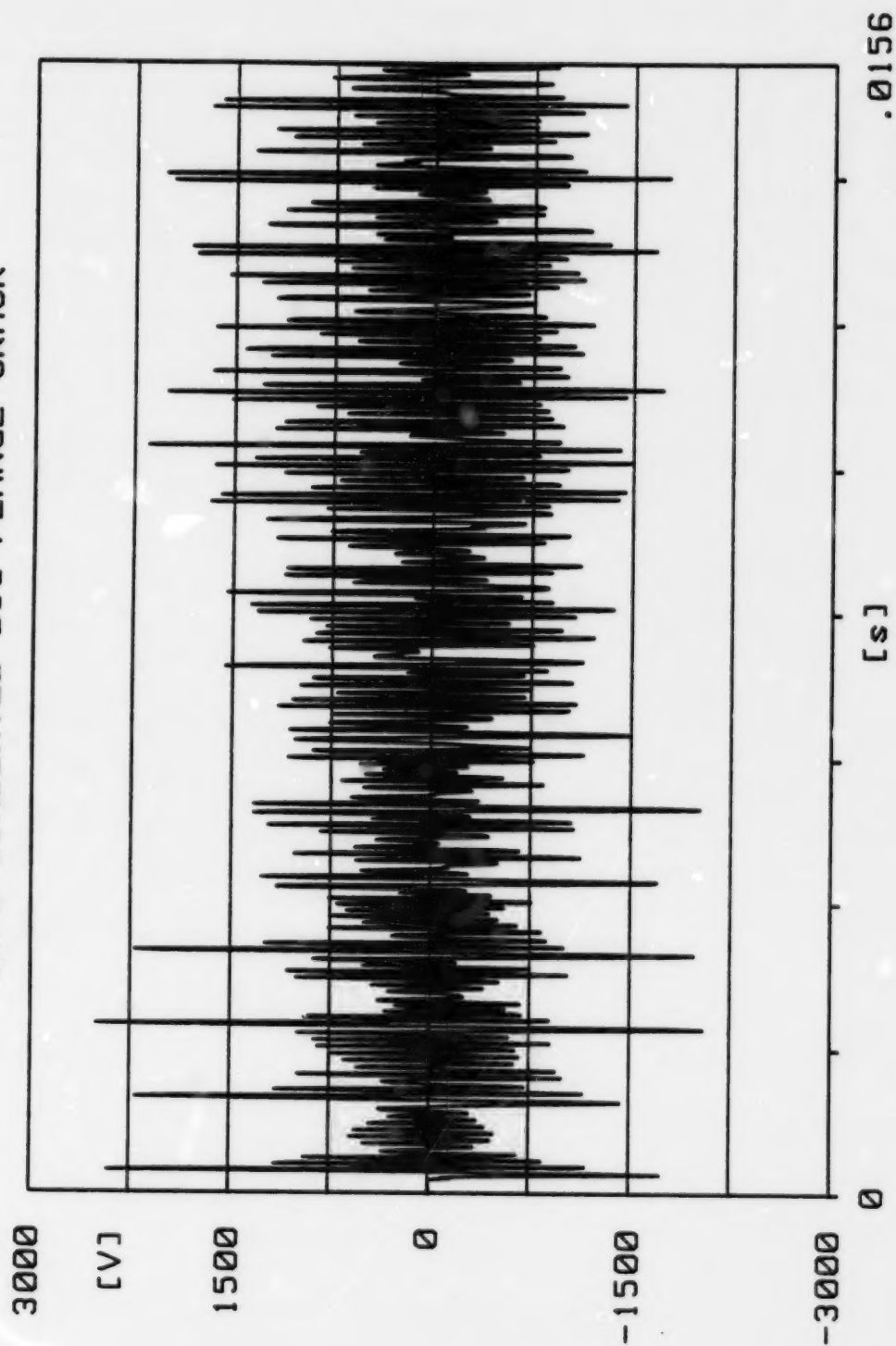


FIGURE 5.27

Auto Spec Ch.A RMS Lin Avg: 1
SH1 GOOD

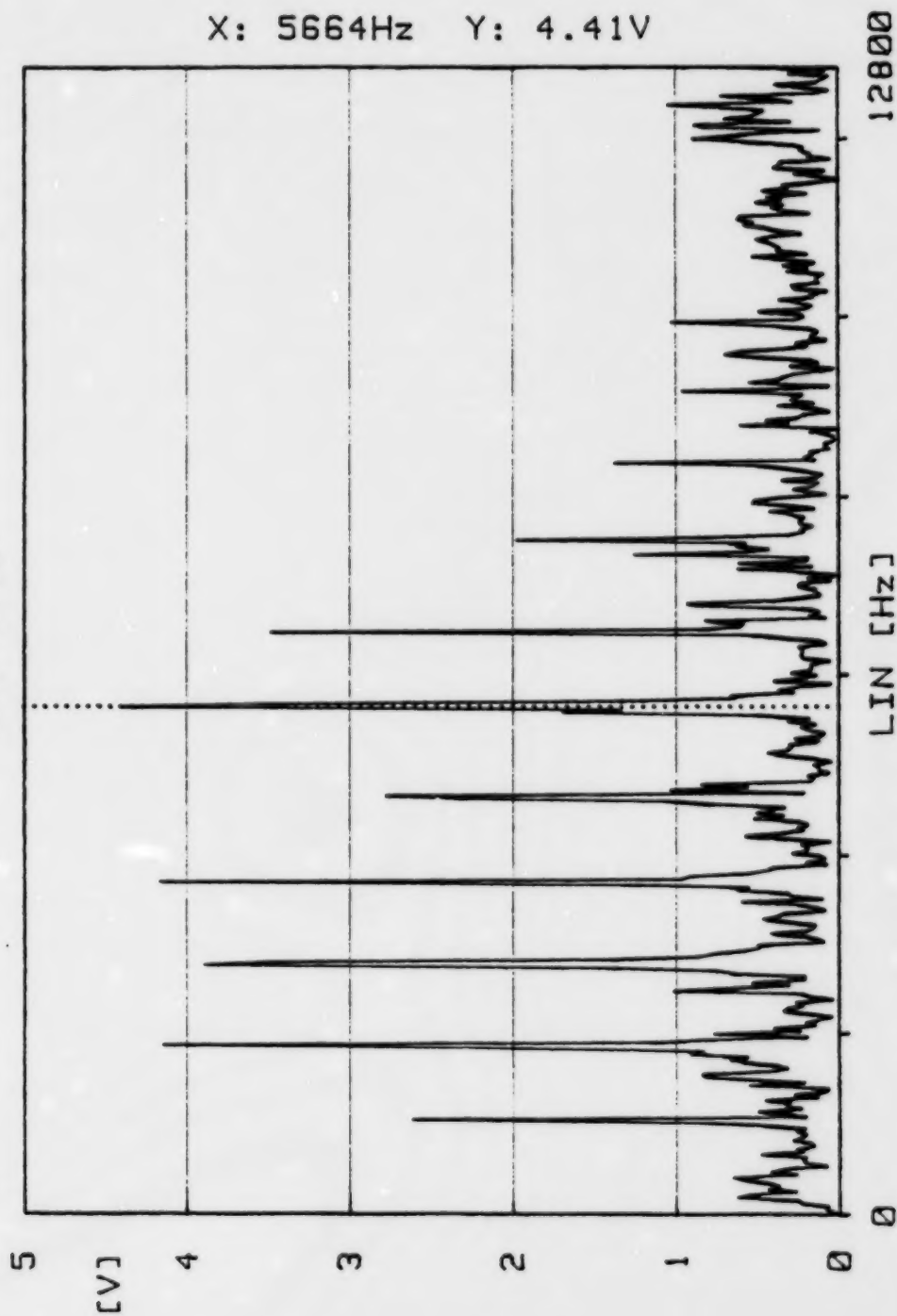


FIGURE 5.28

57C

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Auto Spec Ch.A RMS Lin Avg: 1
SH1 SIMULATED RIM CRACK

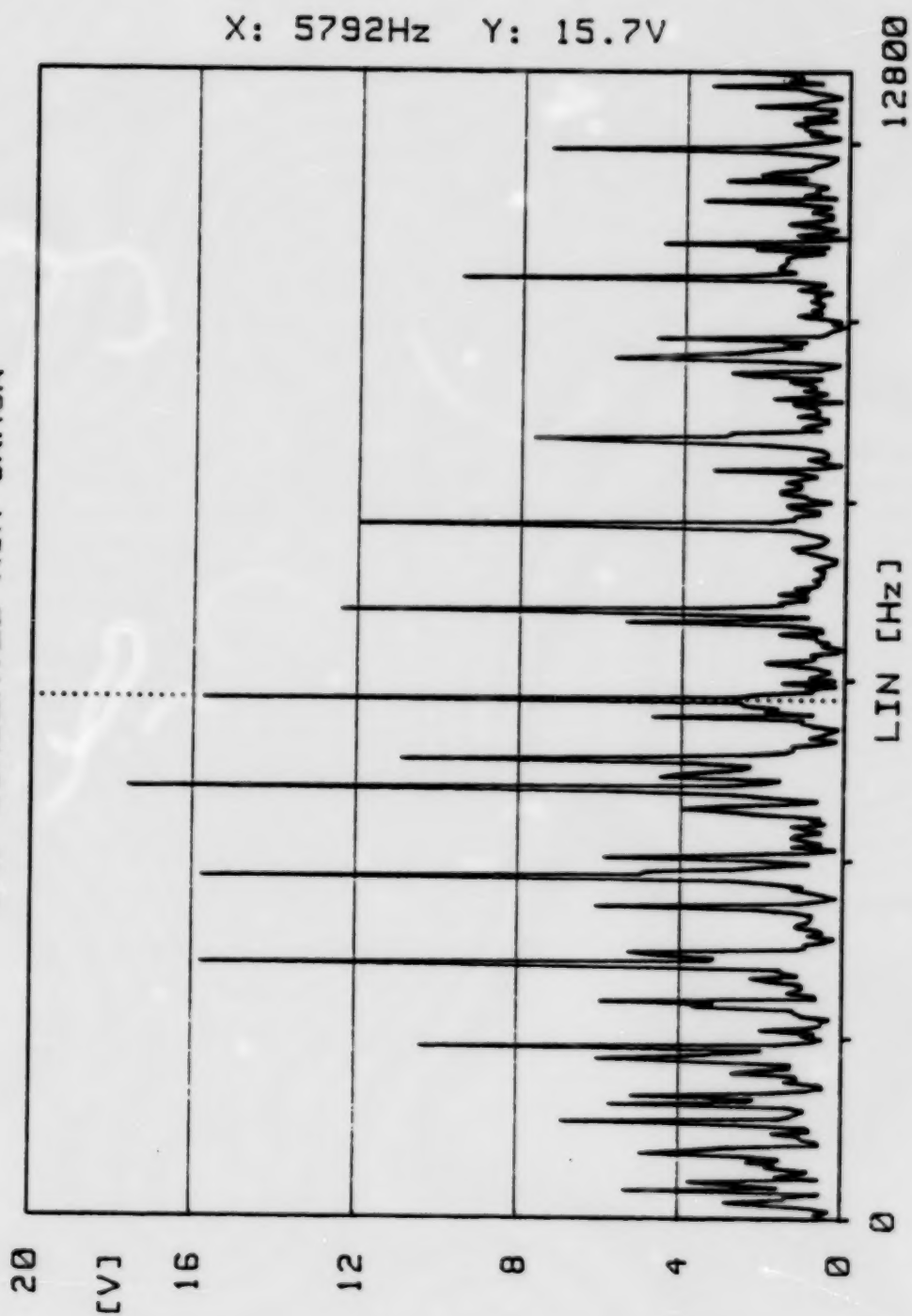


FIGURE 5.29

Cepstrum Ch.A Sp Mag Lin Avg: 1
SH1 GOOD

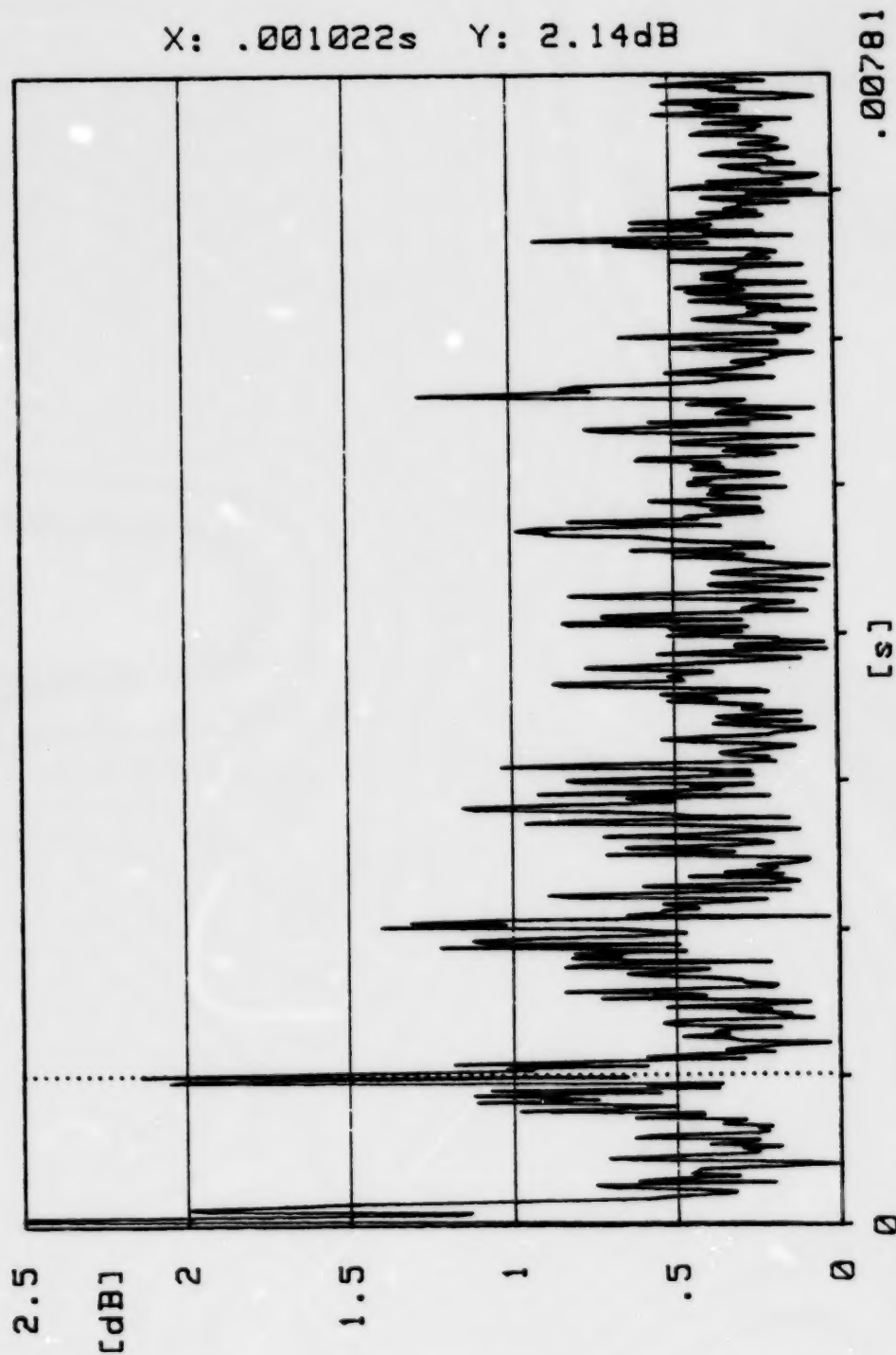


FIGURE 5.30

500

Cepstrum Ch.A Sp Mag Lin Avg: 1
SH1 SIMULATED RIM CRACK

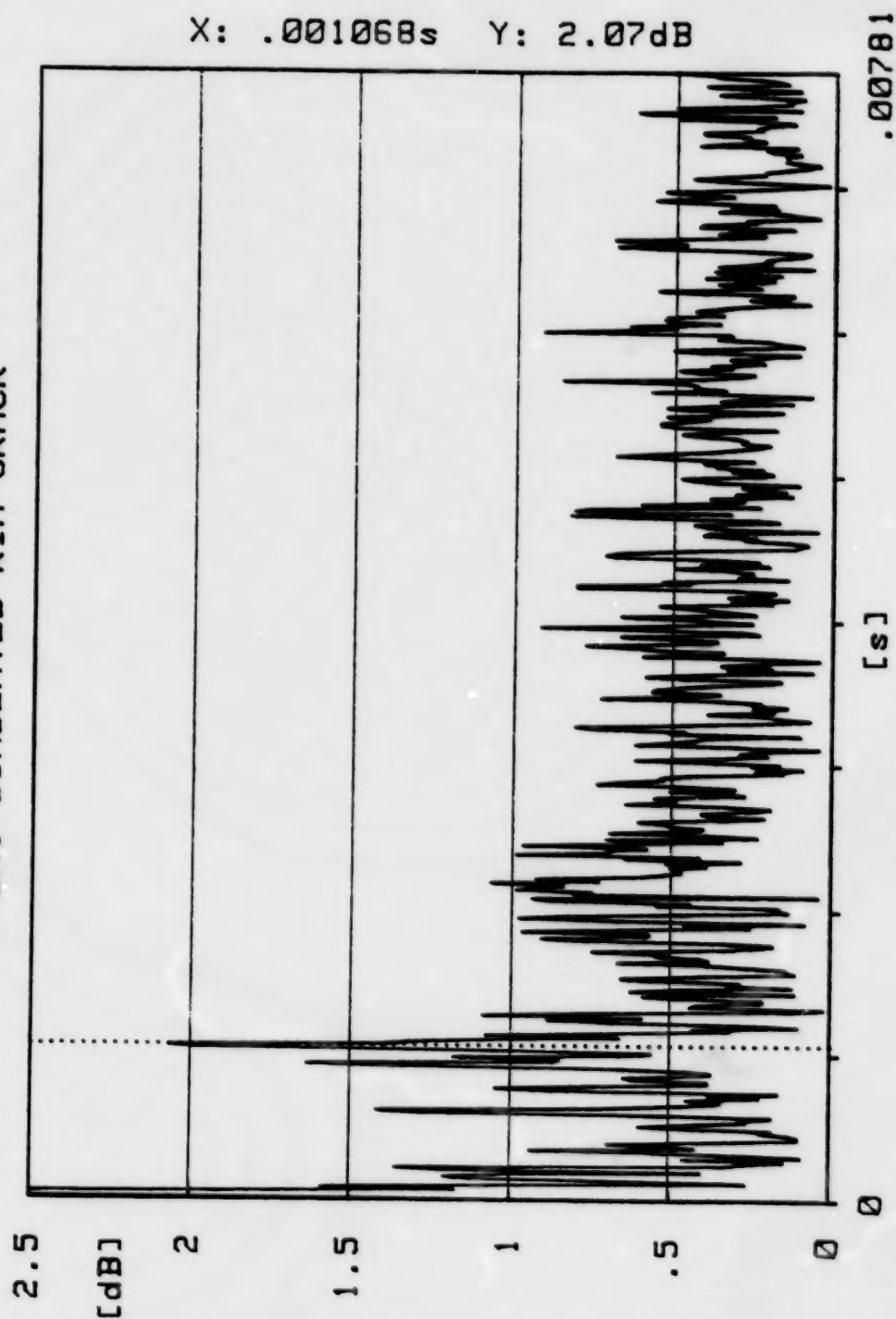


FIGURE 5.31

5.4.3 Effects of a Single Large Rim Crack on Wheel Signature (Cont'd)

and 5.31 present the cepstrum of a good wheel and a simulated rim crack. These two figures are extremely important because they confirm the applicability of this signal processing technique to measure echoes associated with the presence of a crack when a pulse wave propagates around the wheel circumference.

By comparing the two figures (5.30 and 5.31), it can be observed that additional peaks appear within the first millisecond of the signature of the cracked wheel. The major reflections can be identified at 0.6 and 0.9 msec.

5.4.4 Effects of Wheel Surface Defects on the Acoustic/Vibration Signature of a Rolling Wheel on Rail

Based on the tests conducted, it was postulated that a promising approach to detect surface defects on a wheel would comprise installing either a microphone near the track (at or near track level) or installing a vibration pick-up on or near the rail. Either of these two transducers would be used to continuously monitor the signal generated by the wheel/rail contact when a train is passing.

To demonstrate the potential applicability of this technique in identifying surface defects such as flats, built-up tread, shelling, etc., preliminary tests were made on the track available at the CN Pointe St-Charles facility. Ideally, the test track section should have been in near perfect condition so that only wheel defect effects would be picked up. However, for the test results shown in Figures 5.32 and 5.33, track defects were present as evidenced by Figure 5.32 where increases in vibration levels coincide with the presence and magnitude of the corrugations on the rail.

For Figure 5.33, the same track section with a vibration transducer installed on the rail was used, but with a wheelset where built-up tread and a flat had been identified. Many characteristics of the signal may be used to identify the defect type and size: amplitude, time duration of the event or sharpness of the increase (see "flat signal" for example compared to "built-up tread"), frequency content of the noise, etc.

Eventually, the signature of the transducers could also be used for additional functions, such as identifying bearing defects, or used in correlation with other transducers to improve the diagnostic of wheel defects.

SN

Time Ch.B

CN2D GOOD WHEEL, SLOW SPEED, TRACK DEFECTS

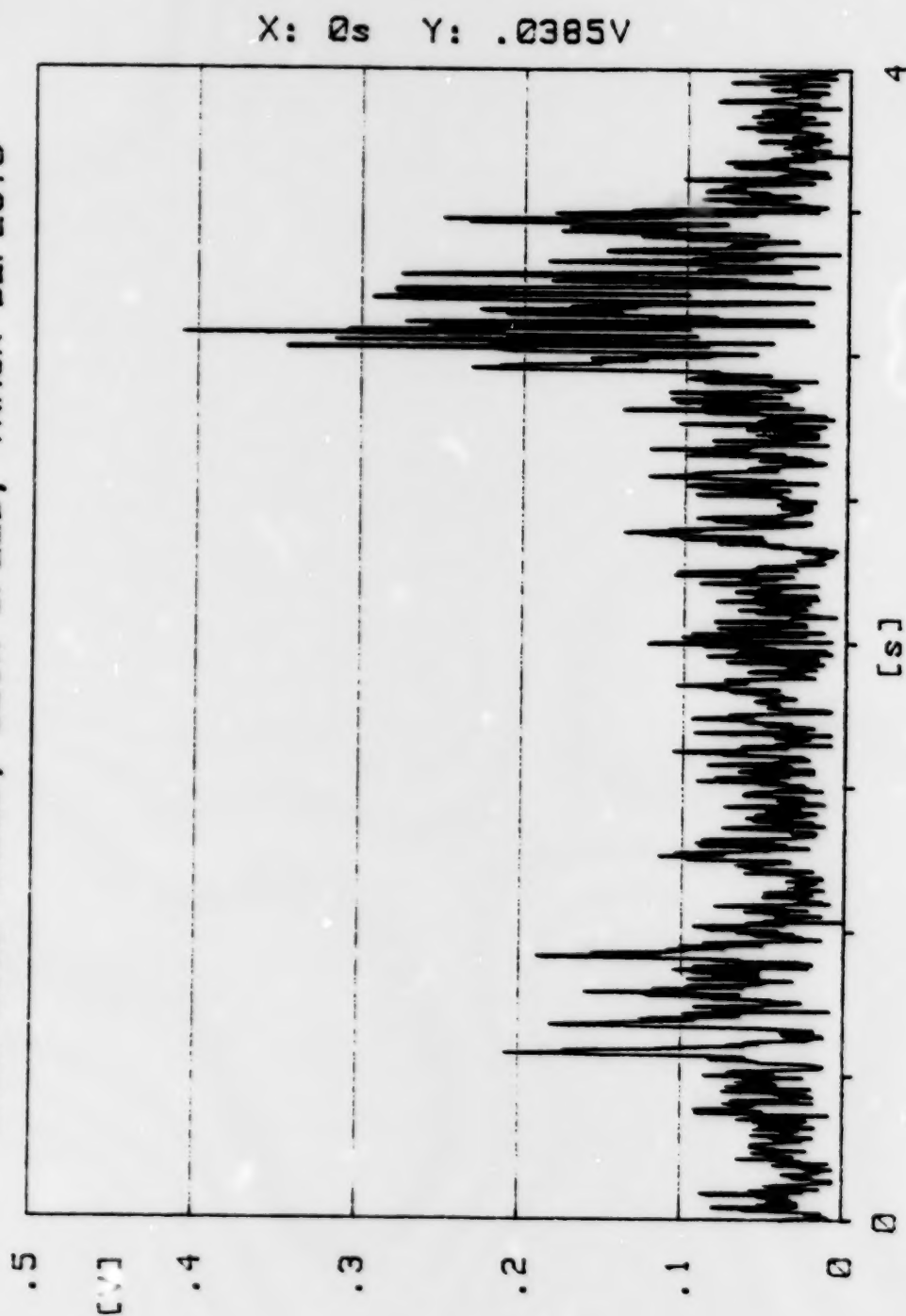


FIGURE 5.32

Time Ch.B

CN4D RAR 78-76, SLOW SPEED, TRACK & WHEEL DEFECTS

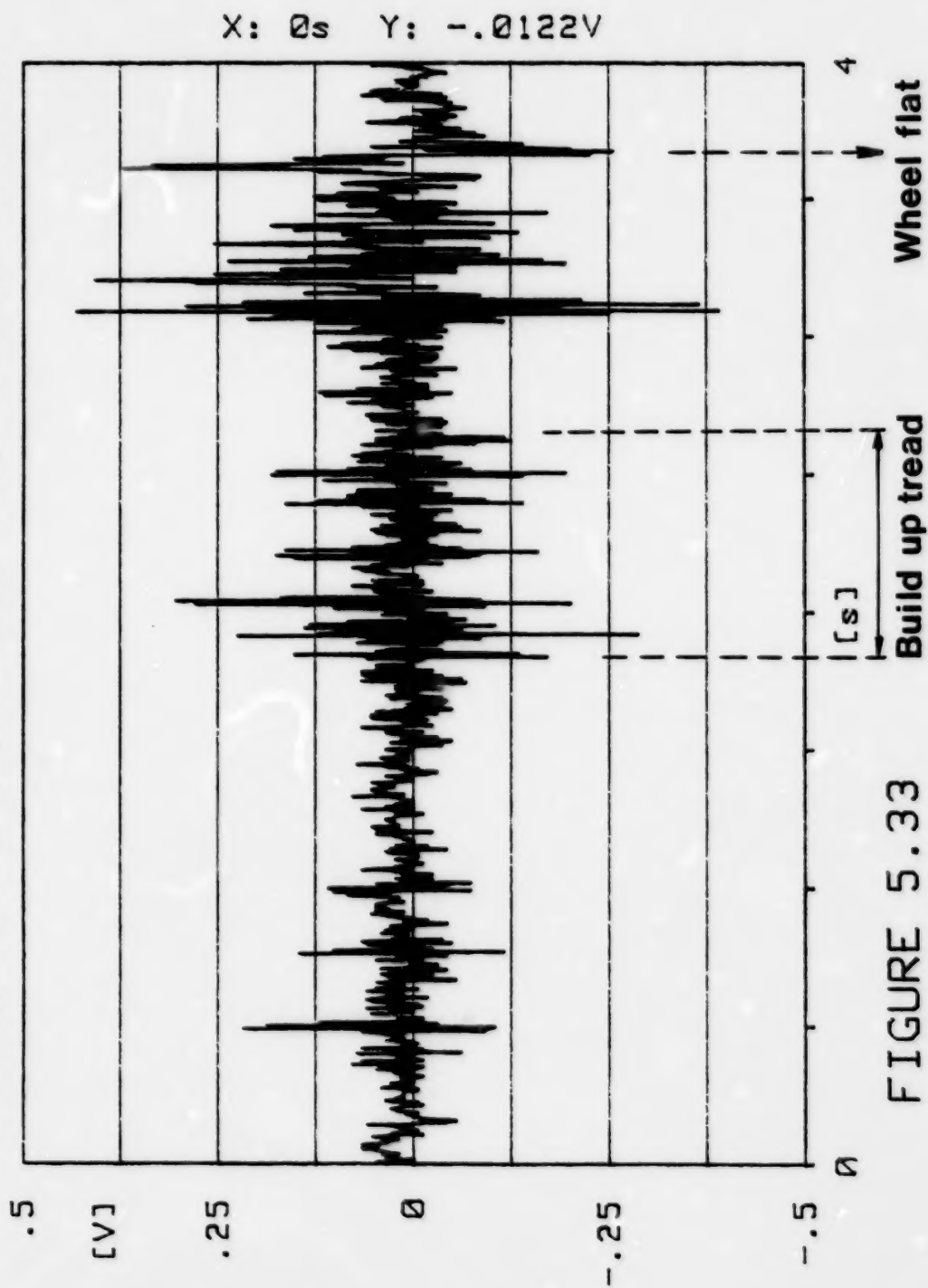


FIGURE 5.33

5.4.5 Other Tests

The test data reported in the preceding sections concentrated on the principal aspects of wheel defect characterization systems.

A significant body of tests was conducted at input frequencies below 10 kHz with "typical" wheels condemned for tread defects. By comparing for example Figure 5.26 (a good wheel) and Figure 5.27 (a condemned wheel), it can be seen that the presence of tread cracks significantly affects the acoustic signature, and a potentially condemnable wheel can easily be identified. However, to condemn the wheel against a specific criteria, e.g. cracks in excess of $\frac{1}{8}$ " depth, the depth must be determined. Appropriate characterization of the defect from the signature proved to be extremely difficult. Difficulties were traced to two causes: (i) there were multiple defects and (ii) the frequency of excitation was too low to permit further, more refined analysis of the signal.

Tests at higher frequencies should be considered.

5.5

Intensimetry

The focus of the test program was the application of intensity analysis, or "intensimetry", as a technology capable of advancing the state of the art in wheel defect detection and identification.

Initial tests showed the superiority of intensimetry in detecting and characterizing plate cracks over other automatic techniques. Tests in the CN shops confirmed this observation. However, as the initial survey showed plate cracks occur far less frequently in service than shelling, small rim, flange and tread cracks, and wear to condemnable limits.

Shop tests at CN and laboratory tests at the University of Sherbrooke, both conducted with excitation frequencies of 10 kHz and below, did not demonstrate any particular advantage in applying intensimetry. Theoretical modelling of the technique by the University of Sherbrooke gave good results, but in practice some masking of the recorded signature occurred when a cepstrum was performed on the data.

Intensimetry remains an attractive technology in part because of its capacity for directional measurement, not possible with single microphone reception. The work of the next phase should address the frequency range above 10 kHz and establish the advantage and limitations of the technique.

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6.0

SYSTEM DESIGN AND PRELIMINARY ESTIMATE OF TARGET COSTS

On the basis of the background survey and test program, it was possible to establish a profile of preliminary equipment requirements for an automatic field wheel crack detection system. These equipment requirements were in turn used to prepare a preliminary cost estimate (Canadian dollars - July 1988) for a possible commercial system, as summarized in Table 6.1.

The postulated system would be part of a general automation inspection facility together with hot box detectors, rail impact detectors and other devices presently under development. The wheel defect system key components would comprise wheel detectors to anticipate the arrival of a train, excitation device, output recording device, computer software and wiring. The complete system would probably involve more than one technology.

To "trigger" the system and determine the speed of the train, two magnetic wheel detectors would be required. It has been assumed that trains may approach from either direction, therefore four magnetic wheel detectors would be required for one crack detector unit. To ensure clear separation of signals for each side of the train, the detectors would be spaced a significant distance apart (some 60 ft. was used by Florida East Coast Railway), in which distance a possible change in train speed would be measurable. Thus, a complete duplicate system or eight magnetic wheel detectors and two wheel defect identification systems would be required.

Although it is too early to define the excitation system, it is evident that excitation will probably have to be in the frequency range above 25 kHz for reliable crack detection, and that a number of appropriate excitation devices and recording devices are available.

It has been postulated that the track installation would be typically at least a kilometer from the yard offices to afford time between defect identification and train separation into individual cars. To ensure a clean signal from the wayside signal processor to the yard output, a 1 km fibre optic connection has been assumed.

It has been assumed that the yard signal processing/interface unit would correlate output with the wheel impact sensor outputs and possibly hot box detectors.

Area lighting and video camera installation would provide a dual function for car identification (for cars with defective wheels), and for general car inspection.

A wayside cabin would provide accommodation for wayside computer facilities and shelter for maintenance personnel.

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TABLE 6.1

Target Cost Estimate

Automatic Field Wheel Crack Identification System

Track-mounted Equipment

Magnetic wheel detectors: 8 @ \$500 ea.	\$ 4,000
Impactor with probe : 2 @ \$3,000/assy.	6,000
Microphones (or accelerometers): 4 @ \$1,000 ea.	4,000
Parallel pair of transducer (ex. ultrasonic, emat)	5,000
Wiring and connection for power and signals	1,000
Ancilliary equipment allowance	5,000
Flange guide, gauge adjustment and general track work allowance	15,000
Sub-total Track Equipt.	<u>\$ 40,000</u>

Wayside Equipment

Dual-channel analyzer	40,000
Computer, including timing base, data communication equipment, printer and video screen	25,000
Cabin, lighting, telephone, video camera, Power (1 km) and maintenance supplies	30,000
Sub-total Wayside Equipt.	<u>\$ 95,000</u>

Yard Output Equipment

Communication Equipment	
Screen	
Printer	
Sub-total Yard Equipt.	\$ 5,000

TABLE 6.1 (Cont'd)

Wiring Track Installation - Yard Output

Wiring/fibre optic lines 1.0 km @ \$10/m	10,000
Transponders/modems 2 @ \$1000 ea.	2,000
Sub-total Data Link	\$ 12,000
 Labour	
Installation	150,000
Start-up and commissioning	25,000
Sub-total Labour	175,000
Contingency (20%)	\$ 65,000
TOTAL	\$ 392,000

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7.0 DISCUSSION

7.1 Technology Assessment

The principal elements of the technology assessment activities were:

- to define the problem;
- to conduct a background study by a review of literature, and contacts (telephone and visit) with researchers and others interested in wheel defect detection systems;
- to review detection technologies and the state of the art of automated defect detection.

Those activities were accomplished and a significant body of data has been amassed.

Problem Definition

From the practical aspect of developing of a viable field system for wheel defect detection, the first questions to be addressed are: What are the defects to be identified? How frequently do they occur? What are the criteria for acceptance or rejection of a damaged wheel?

Detailed statistical data is not available covering all the factors which cause defects in wheels in service. Data that are available show a wide variation in frequency of occurrence of defects.

Representative data for Canadian railroad operations show:

- some 1% per annum of all wheels in service are rejected due to shelling. It should be noted however that there are wide variations between individual railroads;
- 0.03% per annum of all wheels in service are rejected due to development of cracks;
- Subject to type of service:
 - 40-60% of cracks occur in the flange and rear flange face;
 - 10-40% of cracks occur on the tread surface;
 - 5-30% of cracks occur in the rim front face;

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7.1 Technology Assessment (Cont'd)

a small percentage of cracks also occur at other locations including the hub and plate;

- wear and presence of flats are major reasons for wheel condemnation;
- as many as 4% of cracked wheels remain in service undetected and result in train derailment.

Although shelling is the most common problem in its frequency of occurrence, shelled wheels are easily identified. From the point of view of defect identification, the most serious problem is cracking.

Experience by major U.S. railroads is somewhat similar to Canadian experience, though the frequency of defect occurrence per billion ton-miles is higher in the U.S.

Defect Identification Criteria

Minor defects occur frequently and are not a reason to remove wheelsets from service (which would involve significant cost). It is evident, therefore, that some revised criteria for acceptance or condemnation of a cracked wheel would have to be established to take into account the additional data and accuracy which an automated system could provide.

The critical crack depth at which point a crack may propagate rapidly leading to catastrophic failure is not readily defined since it is a function of location, state of residual stress of the wheel, which is in turn a function of wheel history, and wheel loading. Hub and plate cracks may extend for several inches before wheel failure and are thus relatively easy to detect before they become critical. Tread cracks of less than 0.4" have not been associated with wheel failure causing derailment in U.S. experience.

The rate of crack propagation also cannot be readily established and it too depends upon the state of stress of a wheel and its history. Laboratory tests at the A.A.R. have shown that the number of cycles to failure of a highly stressed cracked wheel might be as low as the equivalent of 1000 miles of operation.

7.1

Technology Assessment (Cont'd)

A.A.R. change-out criteria are based on visual inspection and make no reference to crack depth, nor to sub-surface defects. A field system must be able to report defects in a manner compatible with A.A.R. reporting, or the member railroads must agree on some revision to change-out criteria.

It is thus evident that a defect identification system should be able to detect the various types of defects and to characterize them. For example, in the case of cracks, the number of cracks, location, orientation, length and depth should be recorded and made available. Interpretation of this data as to whether a wheel should be condemned, however, should be determined by the railroads.

Background Study and State of the Art

Of all the potential technologies for defect identification, only acoustic and ultrasonic devices have reached the stage of field tests.

Only one acoustic system, developed at the University of Houston, has actually been field tested. Despite a significant effort, the system was never able to achieve an acceptably low false-alarm rate, and the work was discontinued.

Recent tests by SNC suggest that the range of input frequencies used by the University of Houston was too low to identify tread cracks of interest, i.e. those below $\frac{1}{4}$ " in length.

Ultrasonic systems have been installed at the Florida East Coast Railway as operational units. The Deutsche Bundesbahn has tested a prototype system and reported it satisfactory for service use. Both these systems are capable of detecting tread cracks below $\frac{1}{8}$ " in depth, though their ability to detect shelling and flats is not clear. The systems cannot detect hub cracks, plate cracks, some rim cracks away from the tread surface, nor can they detect wear.

To date, no automatic system has been developed which can identify all wheel defects and report them in an appropriate form. Given that derailments continue to occur due to wheel failures, it would appear that the current visual inspection methods are inadequate and can be improved upon by automated devices. Therefore, development efforts to achieve a viable alternative automatic system are justified.

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7.2

Tests by SNC

Extensive acoustic testing was conducted under laboratory conditions at the University of Sherbrooke and in CN Rail's Pointe St-Charles Wheel Shop, with new and defective wheels.

The principal observations made were:

- 1) For mechanical excitation, the form of the hammer is important in determining the input.
- 2) The presence of cracks affects the wheel acoustic signature and defective wheels can be identified; however, below 10 kHz the defect is difficult to characterize.
- 3) Plate cracks with typical lengths of several inches were easily identified at the lower frequencies.
- 4) Further testing is required at frequencies above 10 kHz and in particular at frequencies above 25 kHz for detection of smaller cracks (less than $\frac{1}{8}$ ") to establish the basis for a viable defect detection system.

The review of literature had indicated that satisfactory results were achieved at frequencies of 10kHz and below. Initial work by SNC therefore concentrated in this frequency domaine. However, it became evident as work proceeded that better results were achieved at higher frequencies. That induced vibrations should have wavelengths similar to the typical dimension of a crack of interest became the dominant logic.

- 5) The anticipated advantages of intensimetry were not realized at input frequencies below 10 kHz except for the identification of plate cracks.
- 6) Problems with small tread crack characterization were associated with wheels having multiple cracks. Investigations undertaken to date have concentrated on signal processing to identify a single crack. Obviously, multiple defects in the same wheel must be taken into account in practical systems.
- 7) Flats, shelling and tread build-up can be identified by microphones or accelerometers located at or on the rail, provided the rail is in "good" condition. Signal processing to categorize these defects requires further work.
- 8) As a wheel becomes worn, its resonant frequencies change.

7.2 Tests by SNC (Cont'd)

- 9) The best location for excitation of the wheel is at or near the rail, on the rear face. In theory, it would be better to place the measurement probe at the same location as the impact point. The best location for the measurement probe in practice would be on the front face opposite the exciter.
- 10) Improvement in quality of results for small cracks was noted as the excitation frequency was increased above 10,000 Hz.

The findings with respect to the hammer problems encountered with excitation frequencies below 10 kHz, taken together with the advantages of using analytical rather than comparative signal analysis techniques, suggest that the problem of a high false-alarm rate experienced by earlier researchers may be resolved.

7.3 Future Work

As noted above during the conduct of tests, wear caused a decrease in frequency of resonant peaks. In practice, calibration of this characteristic may prove difficult.

Logically, a developed system should detect all mechanical defects developed by a wheel in service: cracking, shelling, presence of "flats" and wear. More than one technology for defect detection may be necessary to provide an appropriate system. The types of defects and appropriate detection technologies are tabulated below:

TYPE OF DEFECT	DETECTION TECHNOLOGY
Cracks in tread, flange and rim	. echo detection in the output signal of the wheel; . frequencies indicated for investigation to detect a 0.25 inch crack: 100 kHz;
Cracks in the plate	. shift in wheel resonant frequencies; . low frequencies (less than 10 kHz) have to be analysed;
Shelling and tread build-up	. time signal envelope;
Wear of flange, and tread	. physical measurement e.g. by laser.

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7.3

Future Work (Cont'd)

Cracks in the tread, flange and rim pose the most serious problem due to their frequency of occurrence and as the origin of causes of derailments. In order to detect such cracks using surface (or Rayleigh) waves, it has been observed that their characteristic dimension or depth would have to be of the same order of magnitude as the wavelength of the wave propagating around the wheel periphery.

Based on the experimental work conducted at the University of Sherbrooke using ultrasonic transducers, and at CN Rail facilities using acoustic transducers, results showed that the following empiracle relation applies:

$$l = n \cdot \lambda$$

where λ = excitation wavelength

l = crack length

and n = an experimental constant.

In practice, it has been observed that cracks smaller than the wavelength by a factor/varying from 2 to 4 (or greater) have successfully been identified and located in a wheel. The instrumentation used has imposed an artificial limit at $n = 4$. Conversely, it must also be observed that extensive testing to confirm this conclusion has not been conducted nor is there a clear understanding of the interaction between faults and the waves propagating around the weel.

When a wheel is excited by Rayleigh waves which propagate at a velocity of 2930 metres per second, the relation between the crack size and the wavelength is expressed by:

$$\lambda = \frac{2930}{n \cdot F}$$

where

λ = excitation wavelength is millimeters

F = excitation frequency in kHz

n = ratio of the crack depth to the wavelength of the excitation

In practice, if a crack size of $\frac{1}{4}$ " (6.35 mm) is to be detected using Rayleigh waves and a ratio, $n = 4$ is assumed we find that the wheel must be excited at a frequency around 115 kHz.

7.3 Future Work (Cont'd)

The objectives of the phase 2 study would then become.

1. finalize the choice of transducers for signal input (excitation) and measurement of output of the wheel;
2. establish the preferred technology to be used for the various types of defects encountered in a wheel; establish the accuracy and discrimination levels that can be expected;
3. establish the feasibility of these technologies in terms of railroad needs and costs of the system;

The following instruments would be considered for the excitation (input) given to the wheel.

Contacting:

- reversed probes-accelerometer;
- impact hammer;
- acoustic emission (AE) transducer;
- shaker.

Non-contacting:

- electromagnetic acoustic transducer (EMAT);
- reversed probes- non-contacting.

The impactors should incorporate instrumentation to measure and control with precision the excitation given to the wheel.

The following instrumentation (contacting or non-contacting) would be used to monitor the output of (or signal from) the wheel:

Contacting:

- accelerometers (traditional and laser vibrometer);
- acoustic emission (AE) probe;
- electromagnetic acoustic transducer (EMAT).

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Future Work (Cont'd)

Non-contacting:

- microphones (sonometry and intensimetry) which can be used at frequencies up to about 100 kHz);
- accelerometers (traditional and laser vibrometer);
- proximity probe;
- electromagnetic acoustic transducer (EMAT).

In addition to the foregoing, the following should be investigated:

- introduce a delay (by means of an electronic filter) in the measuring instrumentation to obtain a wheel signature based on a unidirectional signal.
- evaluate the vibration levels transmitted to the rail and the interaction between both wheel and rail; evaluate the influence of nearby wheelsets;
- discuss with CN the tests they have made to detect tread defects by means of an accelerometer connected to the rail.

The following items would be required in order to fulfill this test program.

- Bogie with two brand new wheel-sets (axles must be new or certified as having no defects);
- a locker to leave the instrumentation on the site;
- a test site where a rail section could be modified by SNC in order to install an accelerometer;
- additional wheels with single defects of defined size.

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CONCLUSIONS

The general objective of the phase 1 study was to review the state of the technology associated with automatic detection of faults in railroad wheels. The findings of this study have led to the following conclusions:

- There is a need for an automatic wheel fault detection system;
- The preliminary criteria for a wheel defect detection system have been established as follows:
 - . ideally, all defects should be detected comprising cracks at any location, shelling, wear and flats;
 - . a wheel may have more than one defect;
 - . cracks down to $\frac{1}{4}$ " or smaller in depth should be detected;
 - . frequency of inspection should be approximately every 1000 miles.
- No system presently exists to meet these criteria;
- An ultimate detection system would probably incorporate more than one technology (i.e. ultrasonic and acoustic);
- An analytical approach to signal processing based on known, controlled excitation inputs and measured outputs should be used, in addition to the comparison technique mostly used to date;
- The potential for an acoustic vibration analysis system to identify defects has been demonstrated. Indeed, the presence of defects has a demonstrable effect on the acoustic wheel signature.
- At frequencies below 10 kHz, it has not always been possible to characterize defects from the signature, particularly for small cracks.
- Further development is required with inputs in the frequency range 25-100 kHz to develop an appropriate system capable of detecting small thermal cracks. This is potentially within the capability of near-term technology.

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RECOMMENDATIONS

As summarized in Section 7.0 "Discussion", the key findings of this technology assessment study have revealed that effective detection of wheel cracks should not be treated as an isolated inspection function, based upon a single technology. Furthermore, although it had been anticipated that cracks of interest could be identified by analysis of vibrations in the audible range with emphasis on the use of intensimetry, this did not prove to be the case. These findings differ from initial contract expectations, and therefore the detailed statement of work for the following phases of the present study warrants revision as follows:

- .R1 It is recommended that the approach be focussed toward treating wheel defect identification in service as an integral part of train inspection.
- .R2 It is recommended that a wheel defect identification system acknowledge the application of appropriate technologies for specific identification of different type of defects.

In line with these recommendations and the evidence of tests to date with acoustic devices, then:

- .R3 It is recommended that the limitations of acoustic systems be further defined.
- .R4 It is recommended that future contract activities be redefined, and that the scope of work for Phase 2 should be revised as follows:

a) Conduct interviews with the following organizations:

- Fraunhofer Institute (Germany) and J. Cowan (U.S.A.) to discuss the justification of the frequency at which the wheels are tested, their discrimination level and the types of defects detected;
- Canadian National in order to obtain their findings on the detection of defects on the wheel treads, using a rail mounted accelerometer.

The objective of this task will be to complete the information obtained in the first phase.

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RECOMMENDATIONS (Cont'd)

- b) Undertake a structured data acquisition activity to determine the relation between the frequency of wheel excitation and measurement in relation to the crack size.

The objective of this phase will be to establish precisely the range of frequencies of interest for the application of the transducers in order to detect cracks smaller than 1/4 inch with a good reliability without having disturbances from material irregularities (ex. reprofiling marks) which are not of interest.

Once the frequencies of interest will have been established, using piezoelectric and acoustic transducers, the advantages and limitations of the transducers available will be established. A particular attention will be paid to the EMAT (electromagnetic acoustic transducer) system in order to:

- identify manufacturers;
- find a unit which operates in the frequency range of interest (established in the preceding task);
- and, depending on availability of emat transducers, tests cracked wheels to confirm the discrimination level established in the preceding task.

- c) Develop and submit a report covering all activities, findings, conclusions and recommendations resulting from the work undertaken in phase II of the project.

APPENDIX A
CONTRACT WORK STATEMENT

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CONTRACT WORK STATEMENT

The focus of the project is to investigate the use of an acoustic and vibration measurement technology process known as "intensity analysis" in the identification of thermal crack and other faults in railway rolling stock wheels.

The objective of the work is to validate the measurement and data processing systems and determine system capabilities and limitations.

PHASE 1

Work completed during Phase 1 was as follows:

- a) Undertake a critical evaluation of the literature on wheel crack detection systems and document findings. This work shall include an assessment and analysis of available data on wave propagation in wheels.
- b) Arrange and conduct interviews with selected individuals who have undertaken development and/or testing of wheel crack detection systems. In particular, knowledgeable individuals of the following organizations shall be contacted:

- | | |
|--------------------------------|--------------------------|
| - University of Houston | - Griffin Wheel, Chicago |
| - Burlington Northern Railroad | - SNCF, France |
| - Florida East Coast Railway | - CP Rail |

The intent of these discussions shall be to determine the various factors that limited the success of previous efforts to develop wheel fault detection systems.

- c) Undertake an evaluation of the effects of faults (cracks and shelling) on wave propagation to establish the acoustic/vibration characteristics of various faults.
- d) Review various signal processing techniques in support of determining data acquisition and processing methodology to be adopted.
- e) Provide preliminary estimates of target costs for a one-of-a-kind, fully operational system and for possible commercial systems.

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- f) Develop and submit a report covering all activities, findings and conclusions resulting from work undertaken for Phase I of the project.

PHASE 2

Work tasks to be completed during Phase 2 shall be as follows:

- a) Develop and test various types and configurations of impactors with the objective of selecting a design that will provide consistent performance and ensure repeatability of signal initiation conditions.

The impactors shall incorporate instrumentation to measure and control with precision the impact acting on the wheel.

- b) Undertake initial tests of the selected impactor on wheels in various conditions using various transducer configurations and determine optimum arrangements.
- c) Undertake a structured data acquisition activity to determine the influence of the magnitude and location of the impact, type and configuration of sensors and vibration versus sound intensity levels.
- d) Analyse data to establish accuracy and discrimination levels that can be expected.
- e) Determine requirements for post-processing software to identify, provide warning and record presence and size of faults. This activity will involve retesting of wheels to establish the need for software modifications.
- f) Undertake the system design of an in-track fault detection system capable of monitoring the wheels of trains in motion. All components of the system shall be described in terms of performance requirements together with specific technical requirements developed or established during the project.
- g) Reassess system cost estimates provided as item (e) of Phase 1.
- h) Develop and submit a report covering all activities, findings, conclusions and recommendations resulting from work undertaken for Phase 2 of the project.

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APPENDIX B

NOTES ON WAVE TRANSMISSION IN SOLIDS

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WAVE TRANSMISSION IN SOLIDS (REF. 1.7)

Transmission of a disturbance in a gas such as air, a liquid such as water or a solid is commonly referred to as sound transmission. The range of sounds (or frequencies) perceptible to the human ear is normally referred to as the acoustic range. However similar disturbances can be transmitted at higher frequencies, commonly referred to as ultrasonic.

Sound travels from one place to another in the form of waves. Material in some form is always required for the transmission of these waves. The velocity of propagation of these waves is a characteristic of the material. Since the velocity depends principally on the material (and also its temperature) it follows that the frequency of the waves will be inversely proportional to the wavelength. The product of wavelength and frequency will be velocity of wave propagation. What is actually transmitted is a disturbance of some sort in the equilibrium arrangement of the atoms of the material. It is important to note that the material itself does not go anywhere; only a disturbance is propagated. As an example, consider the propagation of a longitudinal sound wave shown in Figure B.1 The dots represent particles of the material that move back and forth under the action of the sound wave.

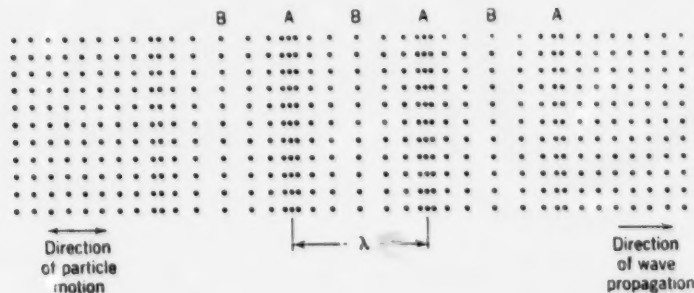


Figure B.1 A Compressional Wave of Sound

The regions labelled A are regions of compression and as a result the density of the material is slightly greater there. The parts of the figure indicated by B are regions of rarefaction and they represent areas of decreased density.

At any given instant, the particles will have a displacement to the right or to the left. The wavelength, λ , is the distance between adjacent regions of a maximum compression or rarefaction. The frequency of the sound wave is the number of waves that pass a particular point per second. An observer at that point with the proper instruments could record periodic variations in several characteristics of the sound wave.

Sound waves act like light waves in many respects, in that they undergo interference, diffraction, reflection and refraction.

In addition to these properties, a sound wave has an attenuation coefficient and a velocity that are dependent on the type of wave and the medium in which it is traveling.

Types of Sound Waves

The longitudinal wave shown in the preceding Figure B.1 is encountered in all branches of acoustic and ultrasonic engineering and can be produced in solids, liquids or gases. It is called a longitudinal wave because the particle motion is along the direction of propagation of the wave.

In solids, it is possible for sound waves to have all or part of their vibrational amplitude perpendicular to the direction in which they are travelling. In an infinite medium, these waves are called transverse or shear waves and there is no longitudinal motion of the particles of the medium. A schematic diagram of this type of wave motion is shown in Figure B.2. A unique characteristic of these waves is that they have no regions of rarefaction or compression. In other words, there are no localized fluctuations in density such as occur in other types of waves. There are other more specialized types of transverse waves. These are surface or Rayleigh waves, Love waves, and plate or lamb waves. Surface waves produce an elliptical motion of the medium, as shown in Figure B.3. The amplitude of the motion decreases exponentially as the depth below the surface increases. At a distance of 1 wavelength below the surface, the amplitude of vibration is less than 10 per cent of that at the surface.

Love waves cannot exist in a wheel and will not be described in detail. This type of wave propagates in a thin surface layer which is lying on top of a substrate consisting of another material.

Waves produced in a plate whose thickness is comparable to the wavelength are referred to as plate or Lamb waves. The two basic types of particle motion in a plate are shown in Figure B.4. The waves that produce these are called symmetrical and asymmetrical waves. The symmetrical wave is similar in some respects to a longitudinal or compressional wave.

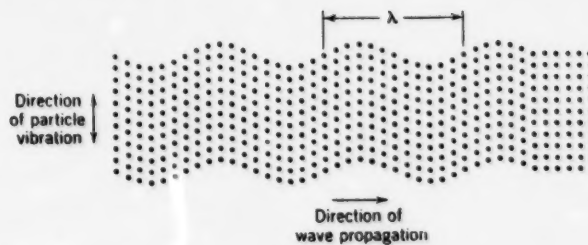


Figure B.2 Transverse of shear wave motion

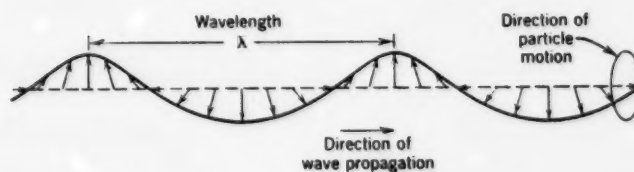


Figure B.3 Surface (Rayleigh) waves

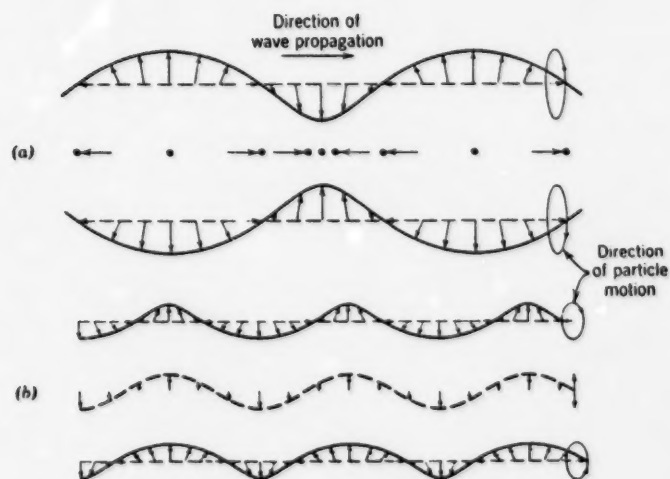


Figure B.4 Plate or Lamb waves. (a) Symmetrical waves. These have some of the characteristics of a longitudinal wave. (b) Asymmetrical waves. These resemble flexural waves (After Krautkrämer).

The asymmetrical wave is a flexural type of wave much like that which is produced by shaking a rug. The particle motion at the centre of the plate is transverse; at the surface it is elliptical, as is the case for symmetrical waves.

The general case of wave propagation in a plate can be considered to consist of a pair of longitudinal waves and a pair of transverse waves bouncing back and forth in the plate from one side to the other. These waves combine in their effect on the motion of the particles in the plate to produce the symmetrical or asymmetrical forms of Lamb waves.

The resulting vibration which can be measured at the surface is the result of the close coupling between the longitudinal (or compression) and shear (or transverse) waves as they travel along the plate.

Each of these components travels at a specific velocity which depends on the type of wave and the density and elastic constants (density, E Young's modulus, poisson's ratio) of the material under consideration.

Table B1.1 lists some formulas for calculating the velocities of various types of sound waves in isotropic material. The formulas for longitudinal and transverse waves assume a medium which is infinite in extent.

Type of material	Type of wave	Velocity, c
Gas	Longitudinal	$\sqrt{\gamma P_0 / \rho}$
Liquid	Longitudinal	$\sqrt{1 / \rho B}$
Solid	Longitudinal	$\sqrt{\frac{E}{\rho} \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)}}$
Solid	Transverse	$\sqrt{\frac{G}{\rho}}$
Solid	Surface or Rayleigh	$\sim 0.02 \sqrt{G/\rho}$
Solid	Lamb	Depends on type and mode.
Solid (long thin rod. Diameter of rod $< 0.1\lambda$)	Longitudinal	$\sqrt{E/\rho}$

where γ = ratio of specific heats

P_0 = static pressure

ρ = density

B = bulk compressibility

E = Young's modulus

ν = Poisson's ratio

G = modulus of rigidity

Table B1.1 Velocities of Various Types of Sound Waves

In the particular case of a steel wheel, the velocities of the various types of waves are:

Wave type	Velocity in m sec ⁻¹
Longitudinal	5950
Shear	3180
Rayleigh	2930

Frequency ranges are commonly referred to as acoustic (0 - 20,000 Hz) and ultrasonic (20,000 Hz to the Megahertz Range).

The wheel analysed in the present study has been considered as whole in the sense that only the input disturbance (impact) or the output (wheel signature) was of interest.

Acoustics

The behaviour of the wheel in terms of the complex wave modes propagating through the wheel, the coupling between the vibration of the wheel surface and the acoustic waves radiated by the surface, etc., are not yet understood completely and are far too complex to be taken into account in the evaluation of the effects of faults on the wheel signature. However, the types of waves propagating in the wheel are of interest.

Following the impact, the vibratory (mechanical or electromagnetic) energy of the excited wheel can be measured directly on the wheel using contacting (accelerometer) or non-contacting probes (laser based accelerometer, proximeter). The signature of the wheel can also be measured using microphones to monitor the sound radiated into the air following impact.

The sound or vibration signal after transduction may be represented in various formats. The simplest of these is an overall RMS sound level. Various weighting networks as well as band-pass filtering may be used to attenuate or excluded noise components in the signal. The frequency spectrum of the signal is a function of the filtering method employed.

In the present study, all the measurements were made with a Bruel & Kjaer dual-channel analyzer which uses the fast Fourier transform algorithm to convert the time signal into the frequency signal.

A narrow constant bandwidth was used in the frequency span of the analyser (0 to 25.6 kHz) in order to improve the perception of signature changes.

Acoustics (Cont'd)

The spectrum of a given wheel signature can then be processed through various digital signal processing available directly on the analyser or programmed with a microcomputer interconnected to an analyser to diagnose whether or not a defect is present.

Ultrasonics

Ultrasonic waves are useful in flaw detection because they can be easily aimed in one direction and can penetrate several feet of metal. This latter characteristic gives them an advantage over X-rays which can travel only a few inches. The technique is also rapid and relatively low in cost. An instantaneous record is obtained and it does not need to be photographed to be seen. The distance of the defect from the surface is part of the information that is provided. This is not readily done with X-rays.

Flaw detection is possible using ultrasonics because sound waves are reflected from a crack or other abrupt change in the elastic properties of the material in which the waves are travelling. Hence, either an echo is detected when a crack interrupts a beam, or the ultrasonic intensity on the far side of the crack is much less or even zero.

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Figure B.5 shows a block diagram of the apparatus needed for flaw detection by the pulse-echo method. A short pulse of electrical waves about 1 or 2 microseconds long is produced by the pulse generator and applied many times per second to a piezoelectric crystal which is attached to the block of metal being tested. The electrical pulse becomes an ultrasonic pulse and travels into the block as shown. Two echoes come back. One is from the far end of the block and the other is from the flaw. When these echoes reach the crystal they generate an electrical signal which goes into an amplifier. The weak voltages produced by the echoes are amplified so they may be seen on a cathode-ray oscilloscope screen. To make the signal bright enough and persist on the screen, the pulses are sent out many times per second. The rate at which they are sent out is synchronized with the sweep of the oscilloscope; that is, when a pulse is emitted, the sweep starts. Echoes appear on the sweep at distances proportional to the travel times to the reflecting surfaces. If no flaws are present, the only echo received is the one from the back surface of the metal.

The time interval for a pulse to travel 1 inch in steel is about four-millionths of a second. This means that to avoid interference between the return echo from a flaw and the echo from the back surface, the former must be short. Pulse lengths of one or two-millionths of a second are in common use for this reason. Even for a pulse duration of 2 microseconds, the pulse is spread out over a distance of about half an inch in most metals.

Ultrasonics (Cont'd)

An important aspect of ultrasonic flaw detection is that energy leaves the crystal or transducer in the form of a beam much like the light from a flashlight. This occurs as long as the wavelength of the sound is a fraction of the width of the transducer from which it came. Since the wavelength at 2 megacycles in metal is about a tenth of an inch, a transducer $\frac{1}{2}$ in. or more in diameter satisfies this requirement and emits a good beam of sound perpendicular to its face.

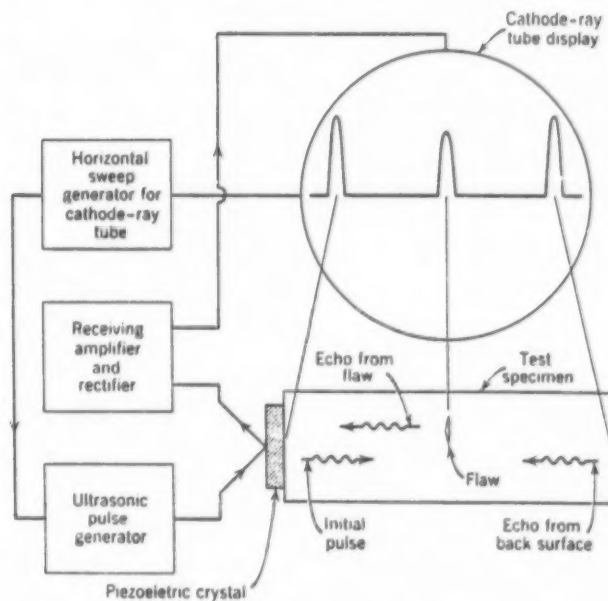


Figure B.5 A Schematic Diagram of a Simple Pulse-echo Flaw Detection System Using a Contact-type Transducer

Ultrasonics (Cont'd)

For the sake of simplicity, the foregoing description has assumed a single piezoelectric crystal attached to the specimen under test. In practice, improvements to this single crystal/direct attachment method are made by immersion and the use of two crystals.

In the immersion type of test, the sound waves leave the transducer, then travel through water and into the test piece. Echoes are returned by the surface, the flaw and the far side of the specimen.

The advantages of this type of testing are that the surface does not have to be as smooth as in the contact type of test, flaws near the surface can be more easily detected, the speed of testing is greater, higher test frequencies can be used, and tests on more complex shapes are possible. This type of test may not be feasible if immersion in a liquid is not possible, or if only limited inspection is required.

Two crystals may be used in either contact or immersion testing. The principal advantage of two crystals is that the transmitted pulse does not momentarily blank out the receiving amplifier since there is no electrical connection between the sending and receiving parts of the system. An additional advantage is that it is possible to minimize or eliminate unwanted echoes or scattered energy by aligning the receiving transducer in a favorable direction for detection of echoes from the flaw.

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APPENDIX C
GENERAL REFERENCES
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LITERATURE REVIEW BIBLIOGRAPHY

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APPENDIX D

MEASUREMENT PROBES CONSIDERED IN PHASE 2

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MEASUREMENT PROBES CONSIDERED IN PHASE 2

In addition to the measuring probes considered in Phase 1 (i.e. microphones and traditional accelerometers), the following transducers will be investigated in Phase 2:

- laser-based accelerometers;
- magnetic and capacitive transducers;
- acoustic emission transducer;
- electromagnetic acoustic transducer (EMAT);
- proximeter;
- ultrasonic piezoelectric transducer.

These transducers were not considered originally in this project because only the audio range of frequencies (20 to 20,000 Hz) were retained. However, preliminary tests results showed that this range of frequencies was not wide enough to permit crack detection of a size down to a quarter of an inch.

Fibre Optic Laser Vibrometer:

A new technology of accelerometers has recently emerged which consists of using optical interferometric techniques (laser beam) for measuring the amplitude, velocity and acceleration of vibrating surfaces. The major advantage of this transducer for our application is that wheel vibration can be measured without contact. Others advantages are:

- high frequency bandwidth (from D.C. or 0 Hz to over 1 MHz);
- high sensitivity;
- high dynamic range;
- very fast response allows detection of transient vibrations;
- small rugged optical sensor heads fit in smaller, tighter spaces;
- easy alignment and operation;
- use of fibre optics in construction allows the processor to be far away from the optical head.

Fibre Optic Laser Vibrometer: (Cont'd)

On the other hand its high sensitivity implies that the probe must be secured in such a manner that it won't be affected by extraneous vibrations (the probe itself).

Magnetic Transducer:

A magnetic transducer is a variable reluctance device which can be used as a velocity sensitive vibration pick-up or as an electromagnetic vibration exciter.

The magnetic transducer is used where changes in vibratory motion have to be detected without contact or added mass, and where absolute amplitude measurements are not necessary. It covers a great variety of applications when used with auxiliary electronic equipment such as counters, time lapse devices, etc.

In conjunction with a signal generator, a magnetic transducer may be used as a vibration exciter.

The magnetic transducer has a high sensitivity and is not influenced by humidity.

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Capacitive Transducer:

The capacitive transducer is a contact-free displacement sensitive pick-up. It finds application where mechanical motion must be detected without loading the test specimen.

This transducer has a high sensitivity and is not influenced by magnetic fields or transducers. It can be used for vibration measurements, displacement detection and counting of mechanical events or time between events with an electronic counter, and as a triggering device.

Acoustic Emission Transducer:

This transducer has a high sensitivity over a very broad frequency range (100 KHz to 1 MHz) so that it can be used for general acoustic emission (AE) detection work.

A typical application of these transducers is to detect and locate cracks in composite materials. The test specimen is stressed and emits noise which indicates the presence of defects in the material under test.

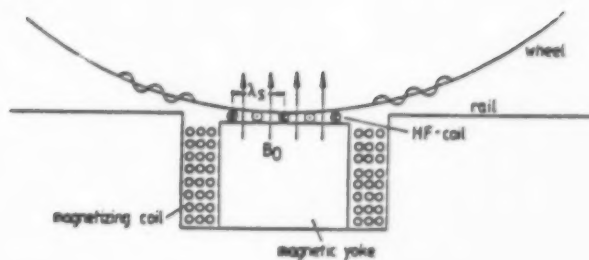
Electromagnetic Acoustic Transducer (EMAT):

This transducer has the capability to act as an exciter or a receiver of ultrasonic pulse (Rayleigh) waves in the frequency range of around 30 kHz to several hundred kHz. The main advantage of this transducer is that no physical coupling is required with the wheel under test even for a signal of several hundred kHz. Also, this transducer is able to radiate the sound energy bidirectionally.

The EMAT transducer is illustrated on the following page. It consists of an electromagnet in the lower part which produces a magnetic field normal to the test area (rail). The HF-coil, which is a meander-like coil, is located on the top of the magnetic yoke. The windings of the coil are oriented parallel to the rail or wheel surface respectively, and are interspersed by the magnetic induction lines. The forces created by this transducer are shear forces alternating with one half of the transducer period λ_s . Such a transducer acts as an angle probe which, for the excitation of Rayleigh waves, is driven below its cut-off frequency for grazing incidence. The ultrasonic wavelength is given by the transducer period λ_s .

The whole transducer assembly consists of one transmitter coil radiating wave pulses in both directions and two pairs of receiver coils. A special coil for 3 MHz CW integrated into the transmitter coil gives the trigger signal for the transmitter generator. Each receiver coil pair consists of two coils which are interlocked with a distance of a quarter transducer period. By this arrangement the two receiver coils detect signals which have a phase delay of -90° or $+90^\circ$, depending on the direction of the wave pulse passing the transducer. These signals are again time-delayed, so that after summation the resulting signal is nearly zero for one direction. For the other direction, the signal amplitude is the sum of the amplitudes of the signals of the two coils. In this way the transducer becomes unidirectional.

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Proximity probe:

This transducer is a non-contacting probe used to measure vibration amplitude, frequency, phase angle, eccentricity and other characteristics of rotating objects. The typical frequency response is 0 Hz to 10 kHz. It is durable (no moving part) and capable of operating in most environments.

This transducer operates on the eddy current principle and senses the distance between the probe tip and the surface it is observing.

The proximity probe generates a radio frequency that is radiated through the probe tip into the observed material, setting up eddy currents. The loss of energy in the return signal is detected by the proximity probe which conditions the signal for linear display on an analyser.

Ultrasonic Piezoelectric Transducers:

These transducers uses piezoelectric (natural or artificially grown) crystals to induce or receive ultrasonic waves. Piezoelectric materials are composed of perfectly aligned dipole cells. Also, when a voltage is applied to them, the dipoles and then the crystal lengthen or shortens, depending on the polarity of the applied voltage, because of electrostatic attraction and repulsion. The magnitude of the effect is proportional to the square of the applied electric field.

The vibratory mechanical force developed by piezoelectric materials is induced by electrical energy having the desired frequency.

The converse effect is also true for these materials; if they are forced by mechanical means to change their length, a voltage appears across the piezoelectric material.

Several ferroelectric (ceramic) materials have been found to exhibit satisfactory properties when suitably processed into a transducer. The most commonly used are barium titanate and lead zirconate-titanate. Most of the transducers use quartz or ceramic materials. The principal advantages of quartz are its mechanical strength and lower internal friction. In all other respects, it is exceeded by the ceramics.

Piezoelectric transducers can practically operate from 20 kHz to several MHz.

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